United States
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ARS-43

June 1986

Long-Range Migration of Moths of Agronomic Importance to the United States and Canada: Specific Examples of Occurrence and Synoptic Weather Patterns Conducive to Migration

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Long-Range Migration of Moths of Agronomic Importance to the United States and Canada: Specific Examples of Occurrence and Synoptic Weather Patterns Conducive to Migration

Edited by Alton N. Sparks

Proceedings of a symposium presented at the combined annual meetings of the Entomological Societies of America and Canada
Toronto, Ontario, Canada, November 30, 1982

Abstract

Sparks, Alton N., editor. 1986. Long-Range Migration of Moths of Agronomic Importance to the United States and Canada: Specific Examples of Occurrence and Synoptic Weather Patterns Conducive to Migration. U.S. Department of Agriculture, Agricultural Research Service ARS-43, 104 pp.

This publication reports the results of several studies on the association of weather patterns in the Southwestern United States and the Gulf of Mexico with the appearance of moths from Texas north to Canada. The moths studied include some of the most economically destructive agricultural pests in North America--sunflower moth, Homoeosoma electellum (Hulst); the black cutworm, Agrotis ipsilon (Hufnagel); the fall armyworm, Spodoptera frugiperda (J.E. Smith); the tobacco budworm, Heliothis virescens (F.); and the corn earworm, Heliothis zea (Boddie).

Keywords: Agrotis ipsilon, biological control (insects), black cutworm, bollworm, corn earworm, fall armyworm, Heliothis virescens, Heliothis zea, Homoeosoma electellum, insect pests, moth migration, moths, Spodoptera frugiperda, sunflower moth, tobacco budworm, tomato fruitworm

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The papers in this publication are edited and revised versions of the papers given at a symposium conducted at the combined annual meetings of the Entomological Society of America and the Entomological Society of Canada at Toronto, Ontario, on November 30, 1982.

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INTRODUCTION

Alton N. Sparks[1]

Although the scholarly literature documents some attempts to manage pests in limited area-wide situations before the mid-1940's--that is, codling moth, Laspeyresia pomenella (Isely 1943); cattle tick, Boophilus annulatus (Say) (Ellenberger and Chapin 1932); cotton boll weevil, Anthonomus grandis grandis Boheman (Cook 1906, Barre 1924)--following the development of organochlorine insecticides, the vast majority of our pest problems were wantonly attacked with insecticides until Rachel Carson's "Silent Spring" (1962). In most cases, we have in the past striven for control of pests on a crop-by-crop, field-by-field basis, and we continue to do so. In general, through the years we have become more sophisticated in our pest management techniques in that regular monitoring of pest conditions has been instituted, and economic thresholds or economic injury levels have been defined as the basis for applying pesticides. This is our defensive concept of pest management. In essence, we willingly forfeit a quantity of our crops to insects until they reach a certain population level or destroy a designated percentage of the crop, and then we grudgingly yield varying quantities of our potential profit to the pests when we try to suppress them on a field-by-field, crop-by-crop basis. Even then, we experience varying quantities of additional crop damage due to miscalculations or to our inability to achieve absolute control of pests.

An alternative to this defensive strategy is to develop an offensive one. Perhaps we should attack our insect pests on an area-wide basis at strategic times and places before they force us to defend our crops on a field-by-field basis. The defensive system of management using broad-spectrum insecticides that simultaneously destroy the beneficial insects that we hope to conserve is a crude strategy. Yet this is the approach we have followed for years. Major improvement is unlikely so long as growers must follow an uncoordinated management system of waiting until the pests have already reached damaging or threatening population levels before attempting control measures. Significant changes in operational strategies are required for major advances in pest management efficiency, regardless of the currently available techniques.

Insect migration is one of the most important remaining mysteries for entomologists to solve before they can deal effectively with the management of most of our economically important agronomic insect pests. This symposium was sponsored by Section F: Crop Protection Entomology of the Entomological Society of America and was convened during the 1982 jointly sponsored United States-Canadian Entomological Societies national meeting held in Toronto. As organizer of the symposium, I selected speakers whose research on migration dealt with highly mobile insect species that are known to have restricted southern overwintering ranges, disperse annually throughout the United States and into Canada, and inflict tremendous economic losses on agricultural crops. The species selected for discussion were: the sunflower moth, Homoeosoma electellum (Hulst); the black cutworm, Agrotis ipsilon (Hufnagel); the fall armyworm, Spodoptera frugiperda (J.E. Smith); the tobacco budworm, Heliothis virescens (F.); and the corn earworm, Heliothis zea (Boddie). Numerous additional species could have been justly selected for discussion. However, the ideas, techniques, and general philosophies of insect migration associated with the five species chosen for discussion here are applicable generally to other important migratory pests.

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Papers concerning evidence for long-range migration of the five species identified above will be followed by a meteorological paper explaining and illustrating climatic opportunities for insect transport. A discussion of the relationship between entomological radar measurements and atmospheric structure precedes the final paper dealing with the economic implications of insect migration studies.

These papers will not become philosophically entangled in a quagmire of semantics concerning "What is migration?," "What is management of insect pests?," "How big is an area?," or question, "Is this research?" Throughout this symposium, authors will consider entomological evidence of long-range migration of five lepidopteran species of insects of economic importance. Climatological and atmospheric conditions suitable for insect transport will be reviewed, and data from radar-observed migratory insect behavior will be correlated with atmospheric data.

Much of the entomological data can be correctly labeled speculative and circumstantial. However, meteorological data show how weather can provide a transport system, while radar data provide information concerning time, height, speed, and duration of insect flight. The combined evidence presents a picture that certainly leads to the conclusion that migration must be considered in any plan for an effective management offensive against highly mobile insects.

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LONG-RANGE MIGRATION BY THE SUNFLOWER MOTH

C.E. Rogers, A.P. Arthur, and D.J. Bauer[1]

Abstract

Southerly wind systems originating in the Gulf of Mexico area move northward over the Great Plains into Saskatchewan, Canada, in 2-3 days. The influx of these southerly winds in northern latitudes during July may be accompanied by significant increases in the number of sunflower moths, Homoeosoma electellum (Hulst), captured in pheromone traps in Saskatchewan. The seasonal entrapment profile for H. electellum on the High Plains of Texas parallels the entrapment profile for H. electellum in Saskatchewan. However, the peak flight activity for H. electellum on the Texas High Plains often precedes either the arrival of moths or the peak flight activity of moths in Saskatchewan by 2-3 days. Evidence strongly supports the theory that sunflower moth outbreaks in northern latitudes of the Great Plains are caused by migrants that are swept northward by strong southerly wind systems that result from continental atmospheric disturbances.

Introduction

The sunflower moth, Homoeosoma electellum (Hulst) (Lepidoptera:Pyralidae), is widely distributed throughout North America, Mexico, Cuba, and Guatemala (Heinrich 1956). The larvae of this species develop in the flowers of several genera of asteraceous plants (Heinrich 1956, Teetes and Randolph 1969a), where they devour pollen, floral structures, and seeds (Rogers 1978) and predispose the capitulum to infection by Rhizopus head rot pathogens (Thompson et al. 1980). The common annual sunflower is the preferred host for H. electellum, but it has also been reared from flowers of several species of native sunflower (Helianthus) that exist in the United States (Rogers et al. 1982). This pest is economically damaging to cultivated sunflower (H. annuus L.) in Canada (Arthur 1978), in the United States (Schultz 1978), and in Mexico (Aburto 1977). Homoeosoma electellum overwinters in median and southern latitudes of the Great Plains (Teetes and Randolph 1970, Rogers and Westbrook 1985). Although there has been an unpublished report of the sunflower moth overwintering at Minneapolis, MN (J.B. Christensen, personal communication), most sunflower entomologists think that resident populations of the moth do not account for its sporadic, heavy infestations of cultivated sunflower in the northern latitudes. Our report is an attempt to document that economic infestations of the sunflower moth in cultivated sunflower in the northern Great Plains and prairie Provinces of Canada may be caused by migrants from southern latitudes of the Great Plains or possibly from northeastern Mexico.

Materials and Methods

Summer wind profile maps for the United States (U.S. Department of Energy, Atmospheric Science Department, Richland, WA) and climatological summaries and weather maps for North America (U.S. Department of Commerce, National Climatic Center, Asheville, NC) were examined to gain an understanding of weather conditions in the Great Plains during the summer months of 1976 through 1979.

The seasonal flight patterns of the sunflower moth were studied in Saskatchewan, Canada, beginning in 1976 (Arthur and Bauer 1981) and at Bushland, TX, from

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1979 (Rogers and Underhill 1983). In Saskatchewan, virgin females were caged in Pherocon ICP traps (Zoecon Corp., Palo Alto, CA) from 1976 to 1978 or with synthetic sex attractants impregnated in rubber septa as lures for traps in 1979 (Underhill et al. 1979). In Texas, only synthetic sex attractants were used in pheromone traps from 1979 through 1981 (Underhill et al. 1982). Traps were placed on (or suspended from) poles either 1.6 m above the ground or on a level with blooming sunflower heads and separated by at least 15 m. Traps were placed in commercial sunflower fields in several locations in Saskatchewan and in grassland pastures and sunflower research plantings at Bushland, TX. Traps were examined at 1- to 3-day intervals (depending on trap location and population levels of moths), at which time moths were counted and removed from traps. Trap bottoms with a soiled sticky surface were replaced as needed to ensure entrapment of moths coming into contact with them. Data on the number of moths caught in the traps were compared with weather data to verify the synchronization of moth flights with continental wind systems.

Results and Discussion

Wind is the dominant weather phenomenon in the Great Plains. Through the millennia, the Great Plains landscape has been molded by the wind; natural flora and fauna have adaptations for survival in the wind; vegetation planted by man is malformed by the wind; pioneers often used windmills to bring subterranean water to the surface for livestock, domestic, and irrigation uses; and several research programs are seeking ways to harness the wind as a source of mechanical power or to use its power to generate electrical energy for agricultural and other uses.

Characteristic wind patterns of the Great Plains consist of a predominantly northerly flow during winter months and a predominantly southerly flow during summer months. A simple summer wind profile for the Great Plains is shown in figure 1. Extensive areas of the Great Plains have a mean wind velocity that exceeds 25 km/h at an altitude of 50 m. However, a greater portion of the Great Plains has a summer wind velocity averaging from 19.3 and 22.5 km/h at altitudes of 10 m and 50 m, respectively. Buoyant objects (for example, small moths) might be carried passively northward by winds at these velocities for 160 to 225 km in 10 h or proportionately farther if suspension time is increased or if active flight accompanies the wind displacement. While short-range to midrange migrations northward might occur at the above wind velocities, it is doubtful that the sunflower moth could often remain suspended in air currents of such velocities long enough to permit its migration from Texas to Saskatchewan. Then we must search for other factors that

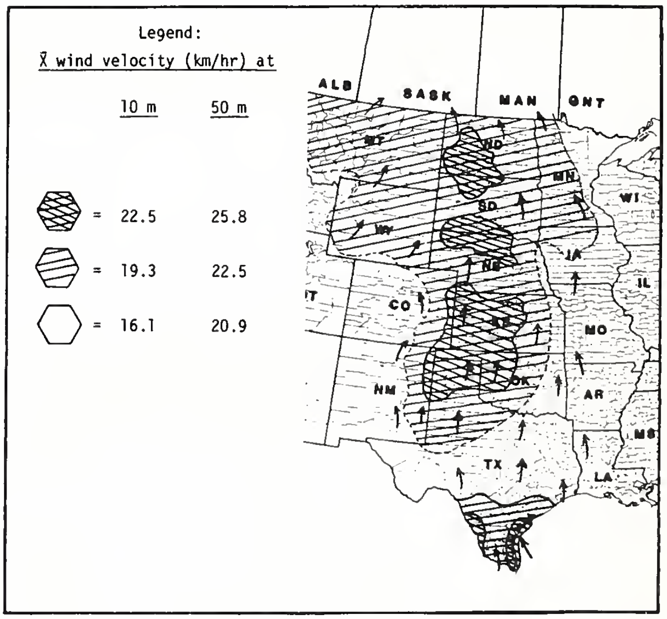

Figure 1
Summer wind profile for the Great Plains of North America. (Note: Arrows flow with the wind.) (Adapted from U.S. Department of Energy, Battell Laboratories. U.S. Wind Power by Seasons [map]).

contribute to long-range migration of sunflower moth populations that result in pest outbreaks.

Another characteristic of the weather in the Great Plains is the frequent and often rapidly moving, alternating, high- and low-pressure systems that cross westerly over the midcontinent region (fig. 2). The clockwise movement of surface air around the rear of departing high-pressure systems and the counter-clockwise rotation of surface air around the face of approaching low-pressure systems during summer months results in surges of warm, southerly air that may travel the length of the Great Plains in from 1.5 to 3 days (table 1).

The passage of successive pressure systems was noted on weather maps, and subsequent airflow patterns were studied. Once the type of weather systems that brought southerly winds to Saskatchewan was determined, similar weather patterns could be recognized and moth movement predicted.

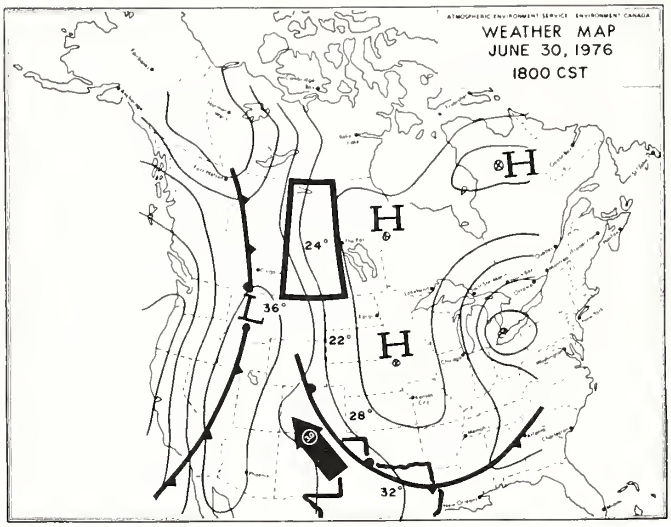

Figure 2
Synoptic continental weather map illustrating atmospheric conditions favorable for the influx of warm, southerly air systems northward across the Great Plains.

Table 1. Characteristics of southerly airflows passing from Texas to Saskatchewan during the summer months from 1976 through 1979[1]

Date and time (CST) airmass--		Temperature (°C) within the airmass	Wind velocity (km/h) range during airmass transit
Departed Texas	Arrived Saskatchewan		
30 June 1976 (1800)	2 July 1976 (1200)	14-32	23-52
30 June 1977 (1500)	2 July 1977 (0900)	17-30	23-57
27 June 1978 (1200)	30 June 1978 (0600)	20-34	18-37
5 July 1979 (1200)	7 July 1979 (1200)	16-32	18-52

[1]Adapted from Arthur and Bauer (1981).

During late June and early July in each of the 4 years, one or more warm, southerly flows developed and moved northward the length of the Great Plains. These flows developed over the Gulf of Mexico, northeastern Mexico, or southern Texas and passed over Texas into southern Saskatchewan in 2-3 days (table 1). In each airflow system, the temperature remained well above freezing, and the wind velocity ranged from 18 to 57 km/h. The average longevity of H. electellum adults is about 10 days in the laboratory at a temperature of 27°C (Randolph et al. 1982). Hence, it appears that atmospheric conditions in these southerly, summer airflows are conducive to moth survival should they become airborne in southern latitudes and be displaced to northern latitudes within 2-3 days.

The synchronizations of H. electellum trapping data with influxes of southerly winds originating over southern Texas are shown in figures 3 and 4. The movement of two distinct flows from Texas to Saskatchewan was monitored in 1978 (fig. 3). The first system passed over central Texas on June 27, 1978, and arrived in Saskatchewan on June 30, 1978. The second system moved from central Texas to Saskatchewan during the period of July 8-11, 1978. The arrival of both these systems was accompanied by significant increases in the number of sunflower moths captured in pheromone traps. A sudden increase in the number of moths trapped about July 25, 1978, indicated the arrival of a strong southerly flow. But weather data were not acquired for that day.

The progress of five large airflows was monitored from southern Texas to Saskatchewan during June and July 1979 (fig. 4). Again, the arrival of each of these systems coincided with a significant increase (5 percent level) in the number of sunflower moths found in pheromone traps at several locations. These and later cases (since 1979) have provided strong evidence that the sunflower moth is

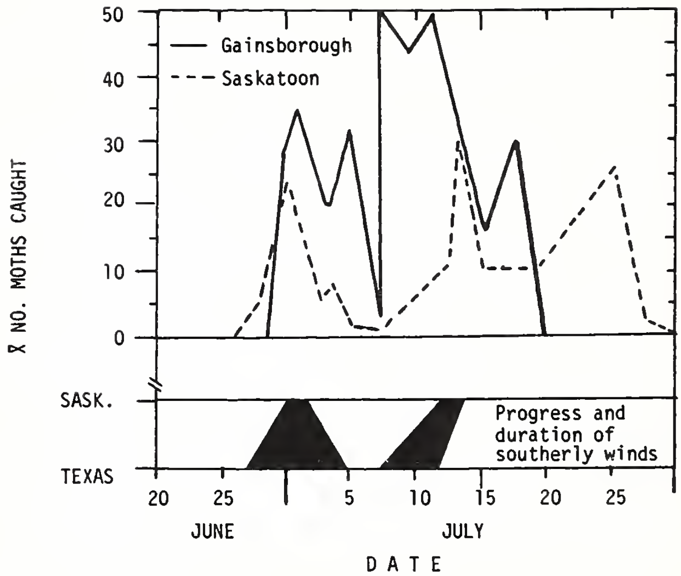

Figure 3
Synchronization of the entrapment of sunflower moths in Saskatchewan with the arrival of warm wind systems originating in Texas in 1978. (Adapted from Arthur and Bauer 1981).

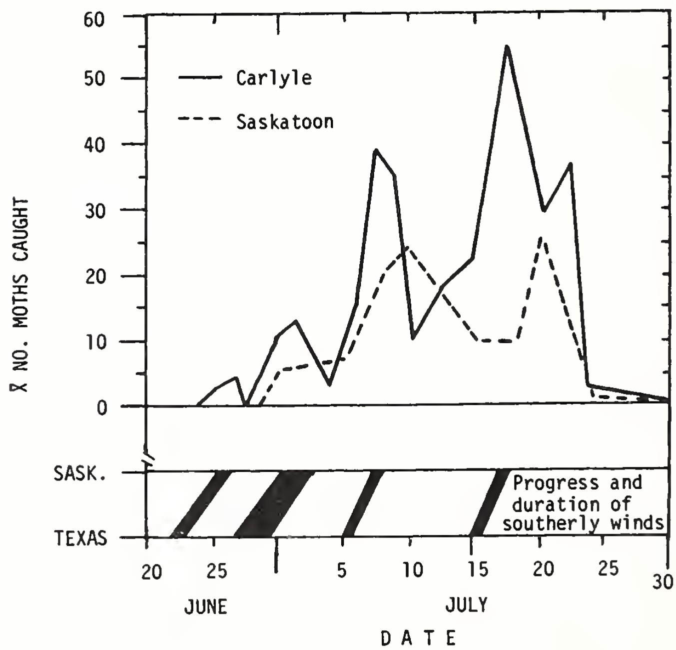

Figure 4
Synchronization of the entrapment of sunflower moths in Saskatchewan with the arrival of warm wind systems originating in Texas in 1979. (Adapted from Arthur and Bauer 1981).

transported into Saskatchewan from southern latitudes by southerly wind influxes associated with the passage of atmospheric disturbances over the Great Plains. The question arises, "Do these atmospheric disturbances also influence sunflower moth infestations in median and northern latitudes of the central U.S. Plains?"

The 1979 seasonal pattern for sunflower moth entrapment at Bushland, TX (about 35° N latitude), and Saskatchewan paralleled very closely. The passage of each of the first three southerly flows over Bushland during June 1979 resulted in significant increases (5 percent level) in the number of sunflower moths captured in pheromone traps located in a grassland pasture (fig. 5). Also, the passage of a strong, sustained system over north Texas in late June and early July 1979 resulted in an outbreak of sunflower moths in blooming sunflower plots and fields. The passage of another southerly airflow over the Texas High Plains in the middle of July 1979 resulted in another sharp increase in the number of sunflower moths found in pheromone traps. The number of sunflower moths trapped at both Bushland and Saskatchewan declined from late July 1979 until early August when both locations again experienced increased moth entrapments, a time for which no wind data were acquired. Another sharp increase in the number of sunflower moths entrapped occurred at Bushland but not in Saskatchewan in early September 1979. However, by late August, northerly winds are beginning to flow down the Plains and may counteract the southerly flows, particularly in northern latitudes, and thus preclude the continued arrival of moths in Saskatchewan. Seasonal moth flight patterns at Bushland since 1979 have not varied by more than a few days as influenced by year-to-year weather deviations (Rogers and Underhill 1983). A consistency that has persisted over the last 4 years is that peak moth entrapment at Bushland, TX, has preceded the arrival or peak entrapment of moths in Saskatchewan by 2-3 days. These observations are further evidence that severe, periodic outbreaks of the sunflower moth through the midcontinent region may result from moth fallout from southerly winds that have their origins in and around the Texas-Mexico coastal areas. For example, sunflower moth populations were smaller than normal in both Saskatchewan and Bushland, TX, during 1982. Synoptic weather patterns during later spring and early summer appear not to have favored the influx of southerly winds over median and northern latitudes of the Great Plains, which may have precluded migration into the more northern latitudes. On the other hand, the southern High Plains and north-central part of Texas experienced unusually strong southerly flows of moist air and persistent record precipitation through June, resulting in losses of several million acres of small grains and

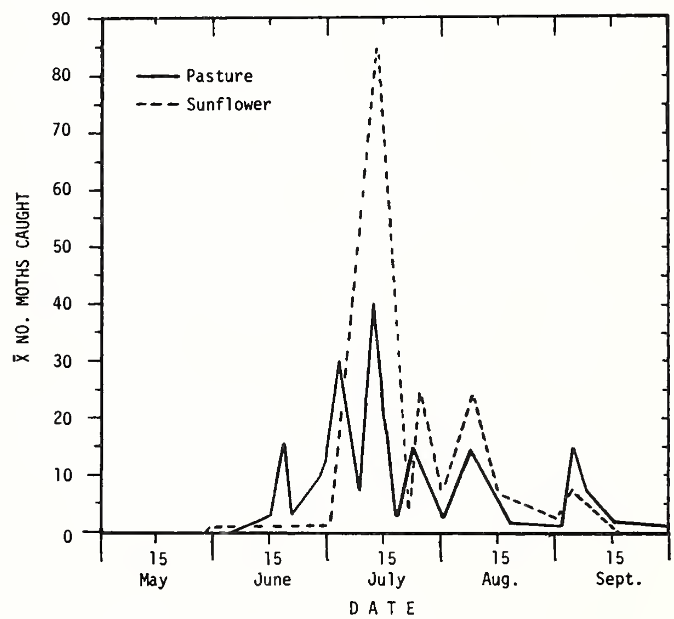

Figure 5
Mean number of sunflower moths caught per trap during the summer of 1979 at Bushland, TX. Data for pasture are for 2-3 nights, while data for sunflower are per night. (Adapted from Rogers and Underhill 1983).

cotton. These systems repeatedly became stalled over central and north-central Texas and its southern High Plains, areas that experienced very high populations of the sunflower moth in 1982.

The long-range-migration theory for the sunflower moth also gains support from earlier research on field-population dynamics. Aburto (1977) reported that severe outbreaks of the sunflower moth occur in late April through early June in northeastern Mexico. Teetes and Randolph (1970) observed that peak adult emergence from overwintering sites occurred in late April through early May at College Station (southeast Texas). Teetes and Randolph (1969b) also found high populations of the sunflower moth on wild Gaillardia in early May and severe infestations on cultivated sunflower from early June through mid-July, at McGregor (south-central Texas).

Hence, adult populations of the sunflower moth appear to be available in sufficient quantity in southern latitudes to permit their being uplifted and moved northward by strong southerly winds. Although much of the data presented here may only be preliminary evidence of long-range migration by the sunflower moth, they give strong support to the theory that severe outbreaks by this species in northern latitudes of the Great Plains may result from migrants via influxes of warm, southerly winds having their origins in the Gulf of Mexico area. It would appear that a detailed study of this question may be of considerable economic value to the U.S. and Canadian sunflower industries.

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EVIDENCE OF MIGRATION OF THE BLACK CUTWORM ADULT INTO THE U.S. CORN BELT

W.B. Showers, A.J. Keaster, J.F. Robinson, and T.J. Riley[1]

Abstract

Circumstantial evidence is presented, based on climatological and biological data collected throughout the central United States, that the black cutworm (BCW), Agrotis ipsilon (Hufnagel), adult migrates to northern Missouri and Iowa, March-May. If the synoptic weather patterns do not produce many nights of strong southerly wind, then few BCW moths will be captured in blacklight traps and few BCW males will be captured in synthetic-pheromone traps in central Iowa. If, however, the synoptic weather patterns include strong southerly winds, there will be an increase in trap captures of BCW moths north of 38° N latitude, with a corresponding decrease in trap captures of BCW moths at 30° N latitude. Circumstantial evidence is also presented that during autumn, the BCW adult enters reproductive diapause at 41° N latitude and that there might be a south migration, but when the migrating adults reach 30° N latitude they again become sexually active. A possible phenology of the BCW in the Corn Belt is developed; premigration (December 22-March 21), migration-infestation (March 22-June 21), postinfestation (June 22-September 21), and reproductive diapause (September 22-December 21).

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Introduction

Rivnay (1964), Spitzer (1972), Zaazou et al. (1973), Odiyo (1975), and Kaster and Showers (1982) have presented evidence that the black cutworm (BCW), Agrotis ipsilon (Hufnagel), is a migratory insect. There has been lengthy debate, however, about whether the damaging larvae in Iowa, central and northern Illinois, and northern Missouri are progeny of overwintering or migrating forms. Puttler et al. (1973) presented indirect evidence that BCW overwinter near 38° N latitude. A preliminary study by Carey and Beegle (1975), conducted near 42° N latitude, suggested that BCW do not overwinter in that region. A definitive study on BCW overwintering was run by Story and Keaster (1982). They determined that at 38°50' N latitude, although adult moths emerged in field cages during September and deposited eggs, few of the eggs were viable. Those that were viable, however, died during late January. The adults did not survive beyond December, and larvae or pupae were not found during the winter and spring.

That Story and Keaster (1982) found few viable eggs substantiates data presented by Kaster and Showers (1982) suggesting that BCW adults in Iowa enter a reproductive diapause during September (fig. 1). On the basis of this evidence and the capture of BCW moths in blacklight traps placed on abandoned oil rigs in the Gulf of Mexico during autumn (Sparks 1979), Kaster and Showers (1982) speculated that a southern migration of this species occurs.

We hypothesize that for BCW migration to occur, a brisk wind blowing from a favorable direction is necessary as well as air temperatures well above 10°C. Also, a wind from other than a favorable direction will suppress long-distance flight. Further, we agree with Domino et al. (1983) that the BCW moths actively seek the wind currents, but we also believe that the moths are carried in air parcels whose

displacement is determined by the wind. When the weather system begins to collapse, however, BCW moths actively descend from the air parcels.

The studies reported here were conducted to determine whether adult BCW could migrate northward on winds during spring and whether a later generation of BCW could migrate southward on winds during autumn.

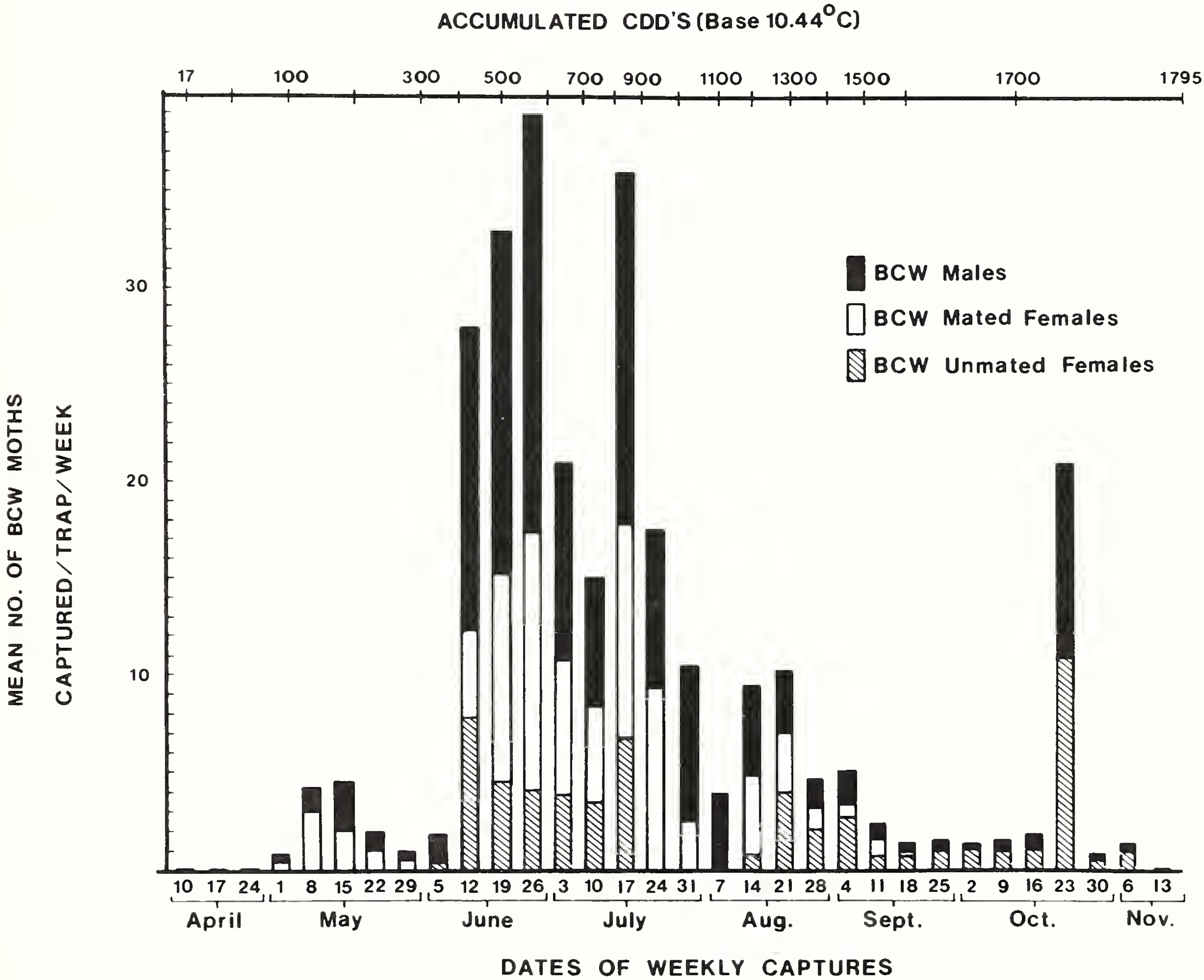

Figure 1
Black cutworm adult captives in blacklight trap, showing female matedness, and accumulated centigrade degree days (CDD), 1979.

Materials and Methods

Meteorological Data

The information gathered from the National Weather Service consisted of wind trajectories (air parcels)--forecasts twice daily (Reap 1972, 1978)--temperatures at 850 mbar (about 1,500 m) (850) and at surface (SFC), and precipitation for 13 stations in the lower Midwest and 15 stations in the upper Midwest (fig. 2). The central United States was divided into lower and upper sections at roughly 38° N latitude.

The systematic Evaluation of Transport ratings presented here are more fully described by Domino et al. (1983) and are based on assumptions consistent with evidence of windborne insect transport (Spitzer 1972, Arthur and Bauer 1981) and knowledge of BCW overwintering (Story and Keaster 1982). Therefore, long-range ratings were arranged north and south of 38° N as 850-N, 850-S, SFC-N, and SFC-S. The 850 ratings consisted of the percentages of maximum possible points scored by the wind trajectories ending at 850 mbar in either the lower or upper Midwest plus points for the 850 mbar temperatures for these trajectories. Also included in the 850 ratings were the surface temperatures and precipitation amounts for National Weather Service stations that the wind trajectories passed over. The surface (SFC) ratings were the percentages of maximum possible points scored by the trajectories ending at the earth's surface plus surface temperatures and precipitation amounts for National Weather Service stations that these wind trajectories passed over. The environmental variables that composed the long-range ratings are summarized in table 1.

Local ratings were composed of climatological data for the Des Moines, IA, National Weather Service station. Rating points were given to the average temperature, relative humidity, windspeed, precipitation duration, and hourly amounts of precipitation for 1800 to 2400 h and 2400 to 0600 h CST each night.

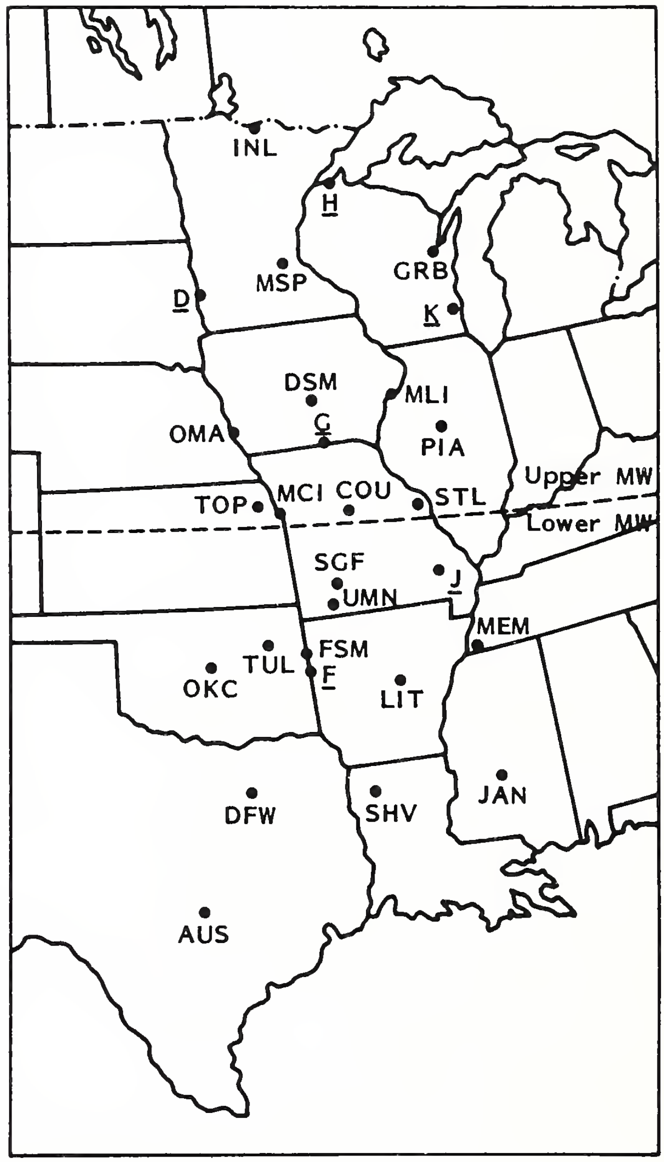

Figure 2
Midsection of the United States divided into upper and lower Midwest (MW), listing weather stations; for example, COU = Columbia, MO, DFW = Dallas-Fort Worth, DSM = Des Moines, MCI = Kansas City, MO, MEM = Memphis, SHV = Shreveport, LA, TOP = Topeka, KS.

Table 1. Long-range rating of climatic variables necessary for migration of black cutworm adults

Category	Subcategory
1. Wind trajectories	A. 850 mbar level --origin of trajectories --curvature --vertical motion
	B. Surface level --origin of trajectories --curvature --vertical motion
2. Temperature	A. 850 mbar level --origin point temperature --terminal point temperature (not used when trajectories rated 0)
	B. Surface --origin point temperature --terminal point temperature (not used when trajectories rated 0)
3. Precipitation	A. Number of night hours with precipitation
	B. Hourly amounts

A long-range rating of 70-100 percent indicated that the trajectories were coming from the south and was called favorable, 60-69 percent was considered marginally favorable, and ≤ 59 percent unfavorable for long-distance BCW moth transport. When trajectories were from other than the south, or when temperatures were less than 6°C, the nights were rated 0 percent.

Local ratings of 80-100 percent were considered favorable, 70-79 percent marginally favorable, and ≤ 69 percent unfavorable for local flight of adult BCW's. These percentages necessary for BCW local flight were based on unpublished data we collected during studies of nocturnal BCW adult behavior.

Additionally, weather systems were taken from daily weather maps, and their positions were typed (Muller 1977) according to the areas they were centered over.

Biological Data

Pherocon 1-c traps, with the sticky surface of each trap covered with Tack-Trap, were baited with 30 µg Z7-12:Ac and 10 µg Z9-14:Ac, the synthesized sex-pheromone system of the BCW (Hill et al. 1979). These pheromone-baited traps (SPT) were stationed 1.5-2.0 m

above the surface near pasture, previous season soybean ground, or previous season corn ground. Trap locations, north to south, were central Iowa, 41°35' N (seven traps); central Missouri, 38°50' N (three traps); southeast Missouri, 36°25' N (three traps); west-central Mississippi, or southwest Arkansas, 33°30' N (two traps); south-central Louisiana, 30°25' N (three traps); and southwest Louisiana, 30°10' N (two traps). Traps were observed and all insects counted and removed three times per week, January-December. The pheromone and the trap tops were changed at 3-4 week intervals, and the sticky floor of each trap was changed at 2-week intervals. During 1979-81, two to seven blacklight (15-W) traps were observed

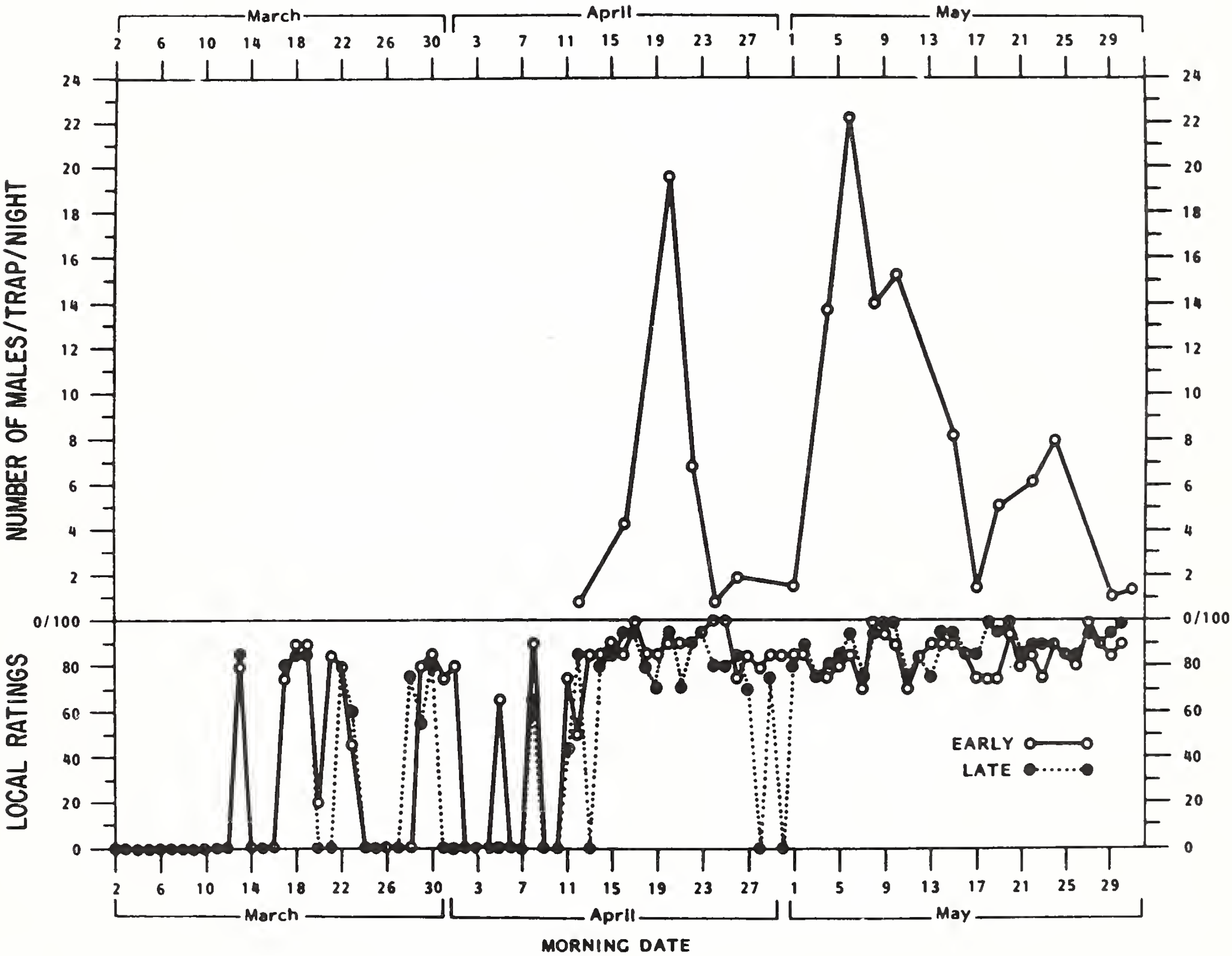

Figure 3
Capture of black cutworm males in pheromone-baited traps in relation to local climatological ratings, central Iowa, 1979. (Early = 1800-2400; late = 2400-0600; Date = morning following capture.)

daily at Ankeny, IA, 41°35' N, and during 1980, two blacklight traps were observed daily at Stoneville, MS, 33°30' N.

Results and Discussion

The data in figure 3 show that, although the local climatological ratings in central Iowa were averaging 80 percent or greater both early (1800-2400) and late (2400-0600) for many of the nights during March 1979, BCW males were not captured until April 11. But immediately after trap placement, an average of two male Lithophane laticinerea per trap were captured March 21, and the average increased to six males on March 30. This species seemingly has pheromone components similar to BCW; therefore, the males are attracted to the pheromone synthesized for BCW. More importantly, however, this species is known to overwinter throughout the Corn Belt among deciduous trees (G. Godfrey, Illinois Natural History Survey, personal communication). Therefore, it is possible that if BCW moths also were overwintering in central Iowa, the local climatological conditions during mid-March (fig. 3) would have allowed some males to seek out the synthetic pheromone and be captured.

Except for the nights of March 16-17, however, the long-range climatological ratings accumulated during March 1979 suggest that the long-range climatological conditions were not adequate to allow transport of BCW to central Iowa (fig. 4). And the April and May captures of BCW males coincide with favorable long-range climatological ratings of 70 percent or greater (fig. 4).

In 1980, beginning with the night of March 10, the March local climatological rating was often above 80 percent (fig. 5). The first L. laticinerea male was captured March 20, and an average of eight L. laticinerea males per trap were captured March 26. But the first capture of BCW males occurred April 7 (fig. 5). As in 1979, if BCW adults were overwintering in central Iowa, then some BCW males should probably have been captured with the L. laticinerea males after the local climatological ratings attained 80 percent over many March nights.

Unlike 1979, however, the long-range climatological ratings indicate that long-range climatological factors during the 1980 spring were not conducive to BCW adult transport. At the same time, trap captures were low (fig. 6). These data provide further circumstantial evidence that potential problem populations of BCW in the Corn Belt originate from migrant moths.

BCW were captured in locations ranging from 30°10' N to 41°35' N latitude. The percentage capture of BCW males per pheromone-baited trap at each latitude during 1979-80 is presented in figure 7, while the numbers of captured BCW moths per pheromone-baited or blacklight trap are presented in table 2. The suggestion by Kaster and Showers (1982) that during autumn in Iowa the BCW adult enters a reproductive diapause allows us to group pheromone-trap captures of BCW males from the central United States into four periods, demonstrating the possible phenology of BCW in the Corn Belt: premigration, migration-infestation, postinfestation, and reproductive diapause.

During the premigration period, a substantial number of BCW males were captured in pheromone-baited traps at 30°10' N and 30°25' N latitude. Thirty-six percent of the annual male capture at each of the two locations occurred during this period (fig. 7). Male capture occurred as far north as 38°50' N latitude. But all captures of males at this location during this period occurred in early March. No BCW males were captured during this period at 41°35' N latitude (table 2, figs. 5-7). During

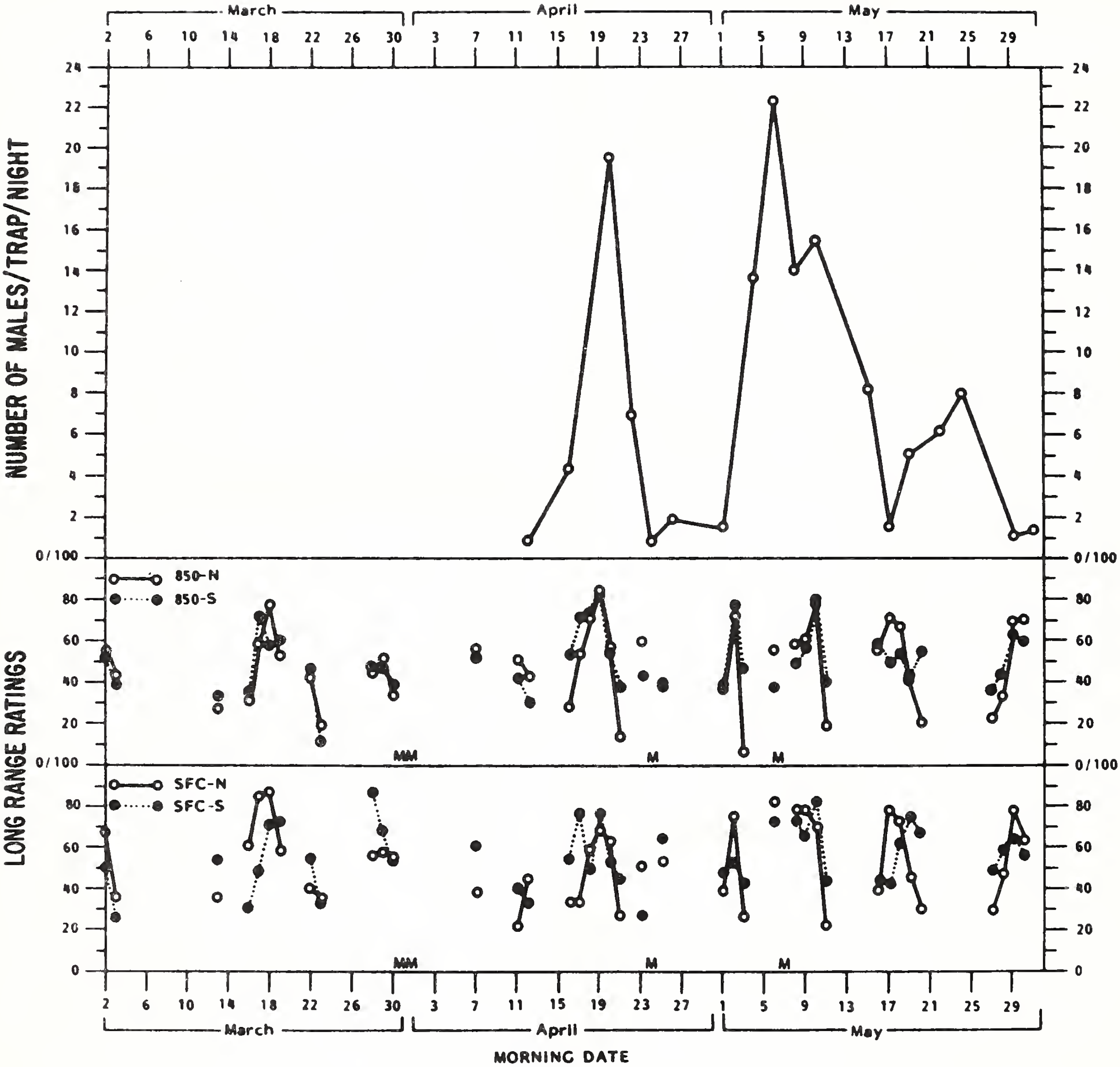

Figure 4
Capture of black cutworm males in pheromone-baited traps in relation to long-range climatological ratings, central Iowa, 1979; nights rated 0 not shown. (M = missing night; Date = morning following capture.)

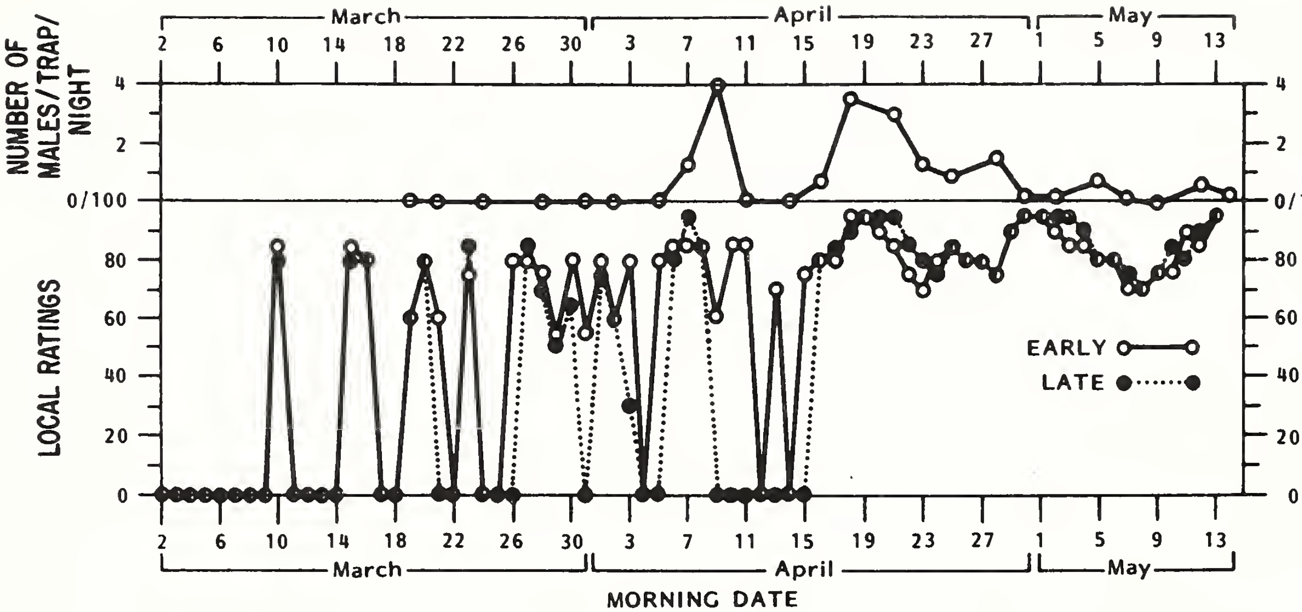

Figure 5
Capture of black cutworm males in pheromone-baited traps in relation to local climatological ratings, central Iowa, 1980. (Early = 1800-2400; late = 2400-0600; Date = morning following capture.)

the migration-infestation period, there was a percentage decrease in capture of males at 30°10' N and 30°25' N, an increase in capture at 33°30' N and 36°25' N, and a dramatic increase in percentage of male capture at 38°50' (55 percent) and 41°35' N (40 percent). During the latter portion (May 20-June 21) of this period at 38°50' N (Columbia, MO) and 41°35' N (Des Moines, IA), the infesting populations of BCW develop to adulthood and, therefore, contributed to the percentages of the migration-infestation period (fig. 7).

During the postinfestation period, all latitudes south of 41°35' N showed a percentage decline in captures of BCW males. At 41°35' N, however, capture of BCW males jumped to 59 percent (fig. 7).

Beginning with the reproductive diapause period of BCW phenology in the Corn Belt, however, there was a reversal in percentages of captured BCW males: just 1 percent at 41°35' N and 9 percent at 38°50' N, while 33 percent of the annual capture of BCW males at 36°25' N (Portageville, MO) occurred during this period. Similar percentage increases occurred at 30°25' N (Baton Rouge, LA) and 30°10' N (Crowley, LA) (fig. 7). However, the percentage capture at 33°30' N (Hope, AK) in hilly topography was intermediate between the Corn Belt locations, Des Moines, IA, and Columbia, MO, and the Mississippi River Delta locations of Portageville, MO, and Baton Rouge, LA, and the Gulf Coastal Plain location of Crowley, LA.

Evidence has been presented that lack of competition from wild females will allow captures of male Lepidoptera in traps baited with synthetic pheromone to be high--that is, when wild female populations are low; likewise, abundant numbers

of females available for mating can reduce the percentage capture of males in traps baited with synthetic pheromone (Oloumi-Sadeghi et al. 1975, Kaster and Showers 1982, Levine et al. 1982). We were concerned that the low percentage of male capture at the more southern latitudes (table 2 and fig. 7) during the postinfestation period might be an artifact brought on by the presence of large numbers of females. Therefore, before interpretation of the pheromone-trap data in table 2 and the percentages in figure 7, blacklight-trap data collected during 1979-80 at 33°30' N and 41°35' N were divided into female and male captures and included in table 2.

The blacklight-trap data show that indeed numbers of females and males captured at 33°30' N declined during the June 22-September 21 period. These data allow us to say that the low numbers of males captured per pheromone-baited trap south of 38°50' N are not artifacts.

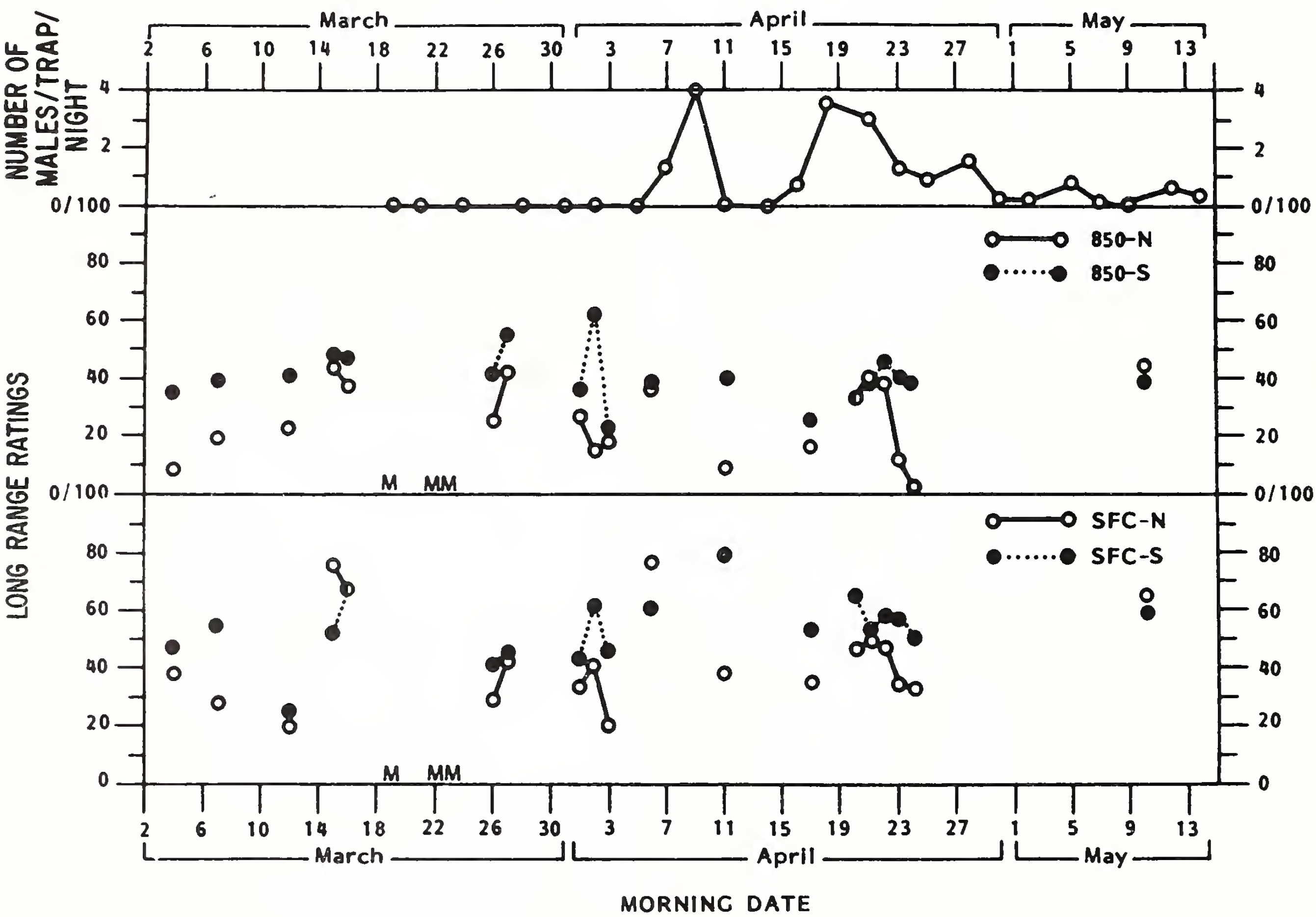

Figure 6
Capture of black cutworm males in pheromone-baited traps in relation to long-range climatological ratings, central Iowa, 1980; nights rated 0 not shown. (M = missing night; Date = morning following capture.)

Of equal importance is the increase in numbers of adults captured in the blacklight traps at 33°30' N during the reproductive diapause period. These data (table 2) suggest a migration of adults from the north.

The small number (1.6) of males captured per pheromone-baited trap at 41°31' N during this period (table 2) is indicative of a behavioral change in the adult BCW at that latitude. The average capture of males in blacklight traps indicates that the numbers available for capture were similar to those for the March 22-June 21 period (migration-infestation). But during the migration-infestation period, just 29 percent of the captured females in blacklight traps were unmated, whereas during the reproductive diapause period, 100 percent of the captured females in blacklight traps were unmated. These data and percentages of female unmatedness agree with the information reported by Kaster and Showers (1982). Whether the low capture of males per pheromone-baited trap at 33°30' N is related to the large number of available females (table 2) during September 22-December 21 or to a behavioral change in the male is unknown. Females captured in blacklight traps at 33°30' N were not observed for unmatedness.

The numbers of males (table 2) and the percentages of males (fig. 7) captured per pheromone-baited trap during September 22-December 21 at 36°25' N, 30°25' N, and 30°10' N strongly suggest that BCW males are sexually active at those southern locations while they are sexually inactive in the Corn Belt.

Table 2. Number of black cutworm males (M) per pheromone-baited trap (SPT) and of black cutworm females (F) and males per blacklight trap (BLT) at specific latitudes, 1979-80

Location/latitude	Dec.22-Mar.21			Mar.22-June21			June 22-Sept.21			Sept.22-Dec.21		
	SPT	BLT		SPT	BLT		SPT	BLT		SPT	BLT	
	M	F	M	M	F	M	M	F	M	M	F	M
Des Moines, IA 41°35' N	0	0	0	108.2	17.2	17.4	161.3	150.6	190.2	1.6	23.2	18.4
Columbia, MO 38°50' N	5.3			42.7			22.3			7.0		
Portageville, MO 36°25' N	11.5			24.4			10.3			23.0		
Hope, AK 33°30' N	18.1	2.0	2.0	24.5	66.0	77.0	8.1	33.0	33.0	9.0	115.0	114.0
Baton Rouge, LA 30°25' N	20.0			15.0			4.5			15.9		
Crowley, LA 30°10' N	27.7			24.0			4.5			21.5		

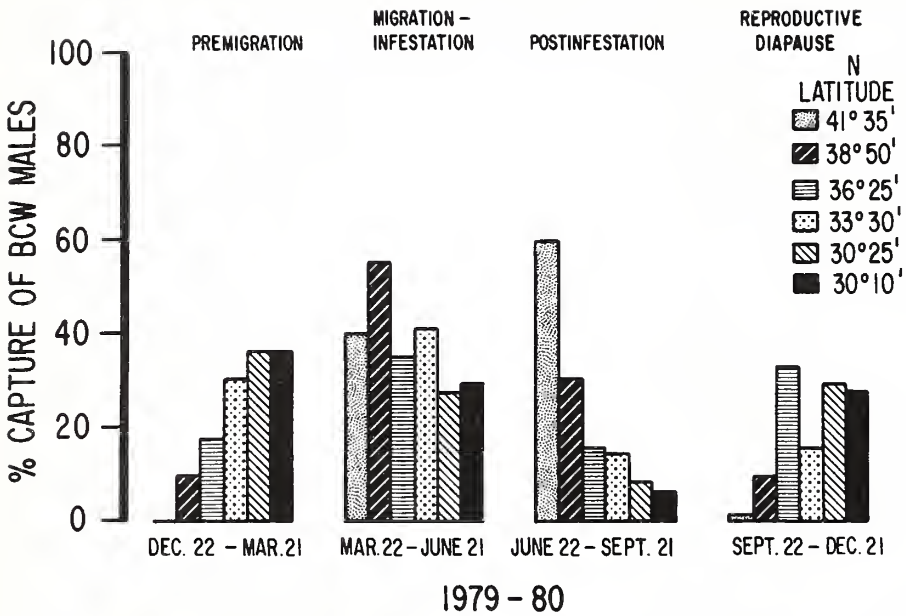

Figure 7
Percentage capture of black cutworm males at six locations (30° N to 41° N latitude) over four seasonal periods, 1979-80.

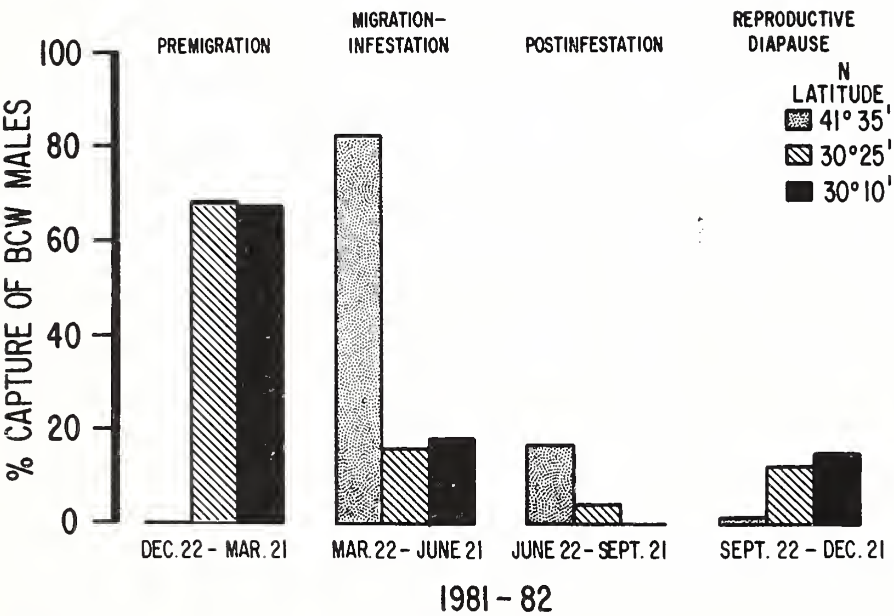

Figure 8
Percentage capture of black cutworm males at three locations (30° N to 41° N latitude) over four seasonal periods, 1980-81.

The pheromone-trap data presented in figures 6 and 7 and table 2 for 41°35' N latitude during the spring (migration-infestation) suggested that 1980 was not going to be a BCW problem year. The blacklight-trap captures (table 2) provided further evidence that few moths came north during that period. During the portion of the migration-infestation period that migration was most likely, there was an average of 16.5 BCW males captured from first capture in pheromone-baited traps until May 15, 1980, compared with 121.5 BCW males captured from first capture in pheromone-baited traps until May 15, 1979.

The 1979 male capture data for first capture until May 15 pales, however, when compared with the 1981 average for first capture until May 15 of 449.3 BCW males per pheromone-baited trap. During 1981, pheromone-baited trap captures of BCW males were recorded throughout the year at just three locations and blacklight-trap captures of BCW at just one location (table 3). Although the numbers of BCW males captured during December 22-March 21 at 30°10' N and 30°25' N were similar to the numbers captured during the same period the previous year (table 2), there was a decline in numbers between years for the March 22-June 21 period.

Again, describing the season with the possible phenology of the BCW in the Corn Belt allows the interpretation that large numbers of BCW adults migrated to 41°35' N from 30° N latitude (fig. 8). The 1981 Iowa Integrated Pest Management (IPM) Weekly Crop Reports (DeWitt 1981) showed that of 300 cornfields sampled, 15 percent

Table 3. Number of black cutworm males (M) per pheromone-baited trap (SPT) at six latitudes and of black cutworm females (F) and males per blacklight trap (BLT) at one latitude, 1980-81

Location/latitude	Dec.22-Mar.21			Mar.22-June21			June 22-Sept.21			Sept.22-Dec.21		
	SPT	BLT		SPT	BLT		SPT	BLT		SPT	BLT	
	M	F	M	M	F	M	M	F	M	M	F	M
Des Moines, IA 41°35' N	0	0	0	550.3	39	67	115.0	119	119	1.0	2	3
Columbia, MO 38°50' N	1.5			18.5								
Portageville, MO 36°25' N	1.3			5.7								
Hope, AK 33°30' N	28.5			15.0								
Baton Rouge, LA 30°25' N	31.5			7.5			2.0			5.5		
Crowley, LA 30°10' N	20.0			5.5			0			4.5		

were heavily infested with BCW; 31 percent, moderately; and 45 percent, lightly. Therefore, BCW were undetected in just 9 percent of the fields sampled (DeWitt 1981).

The percentages presented in figure 8 also show, similar to 1980, that during 1981 few BCW males remained at 30° N latitude June 22-September 21 (postinfestation). The number of males captured in pheromone-baited traps or females and males captured in blacklight traps at 41°35' N during the postinfestation period (table 3) was lower than for the same period in 1980 (table 2). However, whether these lower numbers at 41°35' N latitude during June 22-September 21 relate to the relatively few males captured in pheromone-baited traps at 30° N latitude during the September 22-December 21 period (southward migration) is not as conclusive as the potential for southward migration during the September 22-December 21 period of 1980 (table 2 and fig. 7).

We conclude that the circumstantial evidence for northward migration of BCW adults during March 22-June 21 is substantial. We agree with Domino et al. (1983) that the synoptic weather patterns during this time of year are the key to migration. We also agree with Kaster and Showers (1982) that during autumn, a reproductive diapause might be occurring. But after southward migration during the autumn to the Mississippi River Delta (36°25' N and 30°25' N) and the Gulf Coastal Plain (30°10' N), the adults again become sexually active.

On the basis of these findings, we postulate the overwintering area for BCW populations that migrate to north Missouri, central and northern Illinois, and Iowa to be eastern Mexico and that portion of the United States presented in figure 9.

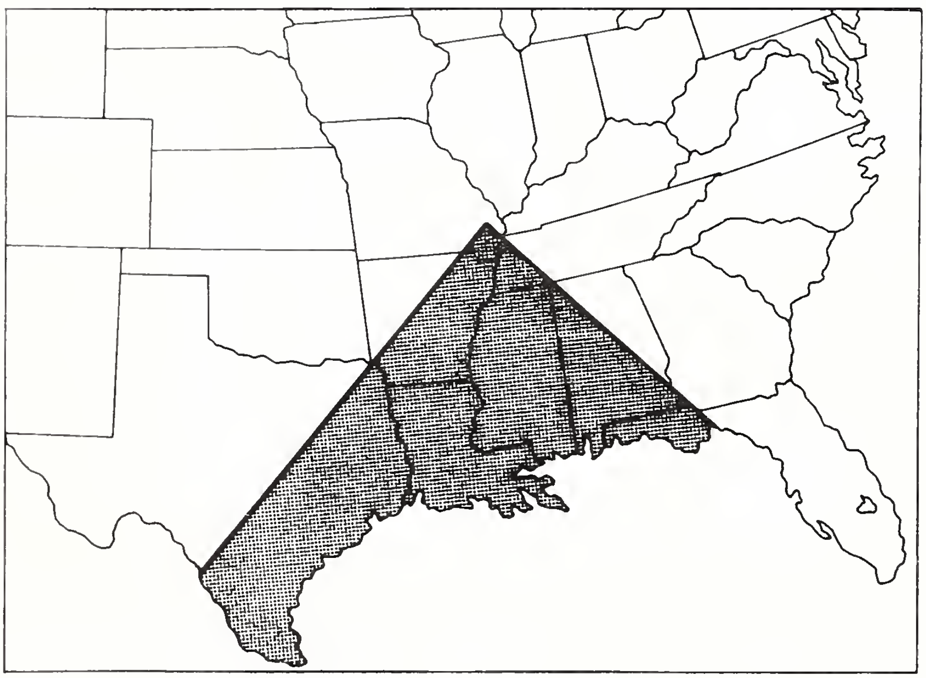

Figure 9
Possible black cutworm overwintering area of the United States that would allow migration to the central Corn Belt.

Acknowledgments

We thank R.P. Domino, former graduate assistant, Iowa State University; T.R. Pfimmer, research entomologist, Bioenvironmental Insect Control Laboratory, U.S. Department of Agriculture, Agricultural Research Service, Stoneville, MS; and W.C. Loe, director, Southwest Branch Station, Agricultural Experiment Station, University of Arkansas, Hope, AK, for assisting in data collection. The research was supported, in part, by Environmental Protection Agency grant R-805429, "Development of Pest Management Strategies for Soil Insects on Corn." This manuscript is Journal Paper J-11043 of the Iowa Agriculture and Home Economics Experiment Station, Ames, Project No. 2280, and Journal Series No. 9396 of the Missouri Agricultural Experiment Station.

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EVIDENCE OF ANNUAL LONG-DISTANCE MIGRATION BY THE FALL ARMYWORM

S.D. Pair and A.N. Sparks[1]

Abstract

Fall armyworm, Spodoptera frugiperda (J.E. Smith), larval populations were restricted to overwintering habitats in Florida below about latitude 27° after the winters of 1981-82. In both years, populations progressed northward during the spring from these areas at varying rates, but they occurred within similar periods. The highest degree of infestations in corn/sorghum was observed in the southerly range of its habitat initially, and these increased in other areas as the season progressed. Initial pheromone trap captures of fall armyworm males were observed earlier in south Florida than in locations removed from the overwintering or source areas. Generally, males were observed during March in Georgia and Alabama and during May and June in South Carolina. Most trap captures at different locations occurred during distinct periods and were associated with weather systems suspected of aiding the aerial transport of migrant species.

Introduction

The fall armyworm (FAW), Spodoptera frugiperda (J.E. Smith), annually inflicts considerable economic crop damage over large areas of the Southern United States and Atlantic seaboard (Sparks 1979). Heavy infestations in late summer and early fall have occasionally been reported in the Midwest and as far north as Canada. Corn, small grains, grasses, and forages are most often the FAW's preferred hosts. But when large populations occur, a wide variety of plant species may be attacked and destroyed (Luginbill 1928, Vickery 1929). Periodically, devastating populations of FAW larvae may literally strip the vegetation bare over wide areas, and such outbreaks have greatly interested entomologists who have studied the pest's biology in an attempt to devise methods for its control. The summer of 1977 is the most recent example of severe outbreaks; damage attributed to FAW amounted to $137 million in Georgia alone (Sparks 1979).

Luginbill (1928) and others observed that FAW appeared on crops in Southern States earlier than in more northerly ones. They surmised that the FAW was migratory, since no diapause mechanism was detected through which winter survival could be accomplished. Such a mechanism has still not been reported; however, cool temperatures may permit intermittent development of immature stages. Research to date indicates that FAW survival during the winter months is restricted primarily to the warm, semitropical areas of south Texas and Florida, although some survival is suspected along the Gulf Coast during mild winters. Studies at different locations in Florida indicate that pupal survival through the entire winter may be possible only in the southern regions (Wood et al. 1979). As the temperature rises and host plants become available each spring, new areas are colonized at an estimated rate of about 480 km/generation, depending on temperature and the prevailing wind direction (Snow and Copeland 1969).

Most accounts of FAW infestations involve particularly damaging populations during the summer and fall with little or no prior knowledge of where the migrants may have originated. However, in the outbreak of 1912, Luginbill received reports of high FAW populations in Cuba in December

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through February of 1911-12 and subsequent high infestations in Florida during early April and in southern Alabama in late April. Hinds and Dew (1915) found heavy infestations at Mobile, AL, in early May 1912 and reported that FAW infestations spread across the State within the month. In the outbreak of 1977, high infestations of FAW in all stages were noted on volunteer and commercial seed corn in Florida during March (U.S. Department of Agriculture 1977).

Little is known about the actual migratory capabilities of the FAW or of the influence of weather, particularly of wind-aided transport. From 1926 to 1957, Glick (1965) captured FAW in airplane nets at altitudes of 152 to 610 m in Louisiana. Rose et al. (1975) reported a massive flight of FAW into Sault Ste. Marie, ON, and concluded through backtrack analysis of wind trajectories that their flight originated in the lower Mississippi Valley, a distance of 1,600 km. In 1973, A.N. Sparks and R.D. Jackson (unpublished data) mounted light traps on unmanned oil rigs in the Gulf of Mexico and, after passage of cold fronts, captured FAW as far as 160 km from land. Even though less than optimum conditions may be present, FAW can maintain flight at temperatures as low as 10.6°C (Carpenter et al. 1981).

Current Research

The seasonal distribution of FAW has been described using U.S. Department of Agriculture Cooperative Insect Survey Reports (Snow and Copeland 1969), and Waddill et al. (1982) reported on the seasonality of FAW populations at four locations in Florida. However, the delineation of FAW overwintering habitat and the subsequent movement from these areas each spring has not been addressed in detail, particularly in regard to the influences of weather.

In 1981, we began a long-term program to delineate FAW overwintering areas in Florida by larval surveys and a network of pheromone traps. This program was also designed to determine the time and rate of movement of FAW populations from those areas to other States in relation to weather. Reported here are our preliminary results from these studies.

Pherocon 1C and 50-25 cone traps (Hartstack et al. 1979) baited with 25 mg of Z-9-DDA (Mitchell 1979) were positioned at several locations throughout Florida, Georgia, and South Carolina in 1981; Alabama was included in 1982 (fig. 1). During early spring each year, corn was

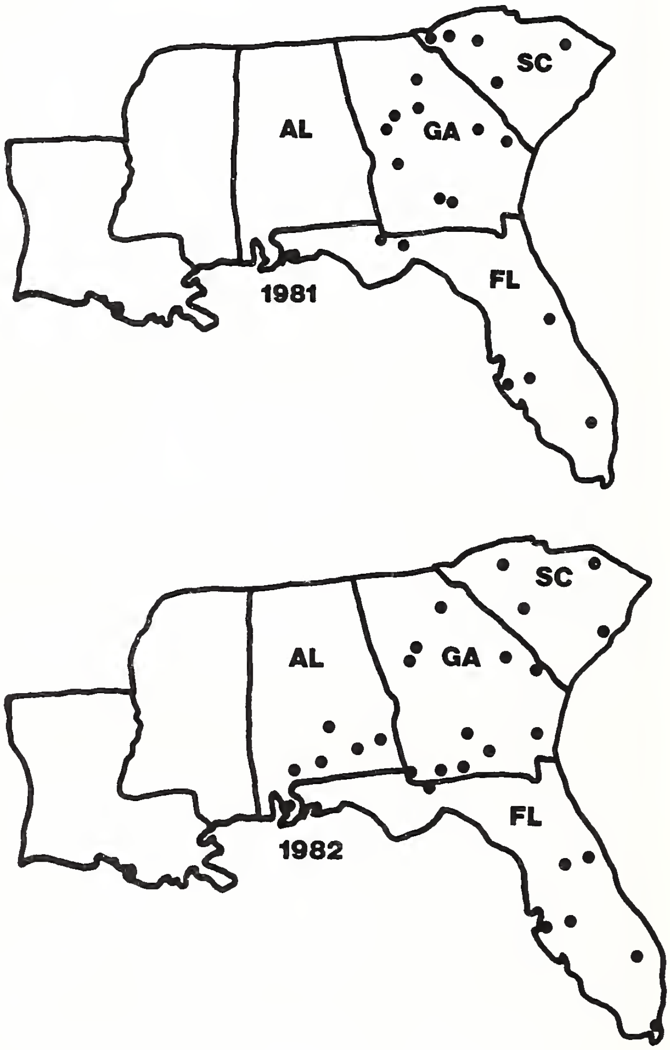

Figure 1
FAW pheromone trap locations, 1981-82.

surveyed in south Florida and in more northerly areas as the season progressed. Infestation levels were determined by counting the number of infested corn or sorghum plants on 4 m of row at four locations per field. Where volunteer corn was encountered, 50-100 plants were selected at random and examined for FAW eggs and larvae. We attempted to sample at least one corn/sorghum field about every 80 km in the course of a survey. In these surveys, plant species other than corn or sorghum were rarely attacked until preferred species were either destroyed or no longer attractive. Therefore, efforts were concentrated on these two crops where they occurred. Infestations in each sampling area were assigned a number, on a scale of 0 through 5, that reflected the relative degree of infestation in each area as follows: 0=no detection, 1=1-5 percent, 2=6-25 percent, 3=26-50 percent, 4=51-75 percent, and 5=76-100 percent.

Spring Movement, 1981

Polar air invaded much of Florida during January 1981 and caused subfreezing temperatures as far south as Miami. As a result, most of the available hosts, such as volunteer corn, were destroyed by frost. The date of first pheromone trap catches of FAW males in the ensuing months (beginning in March) are shown in figure 2. The date of observed catches during March in south Florida may not have reflected the actual first appearance of FAW males, since most traps were positioned in early March. However, populations were very low at that time because of cold spring temperatures that persisted throughout Florida. Indeed, males were not captured until early and mid-April in central and north Florida, respectively. By late March and in April, FAW males were observed in traps at all the Georgia locations. In South Carolina, FAW were not detected until May.

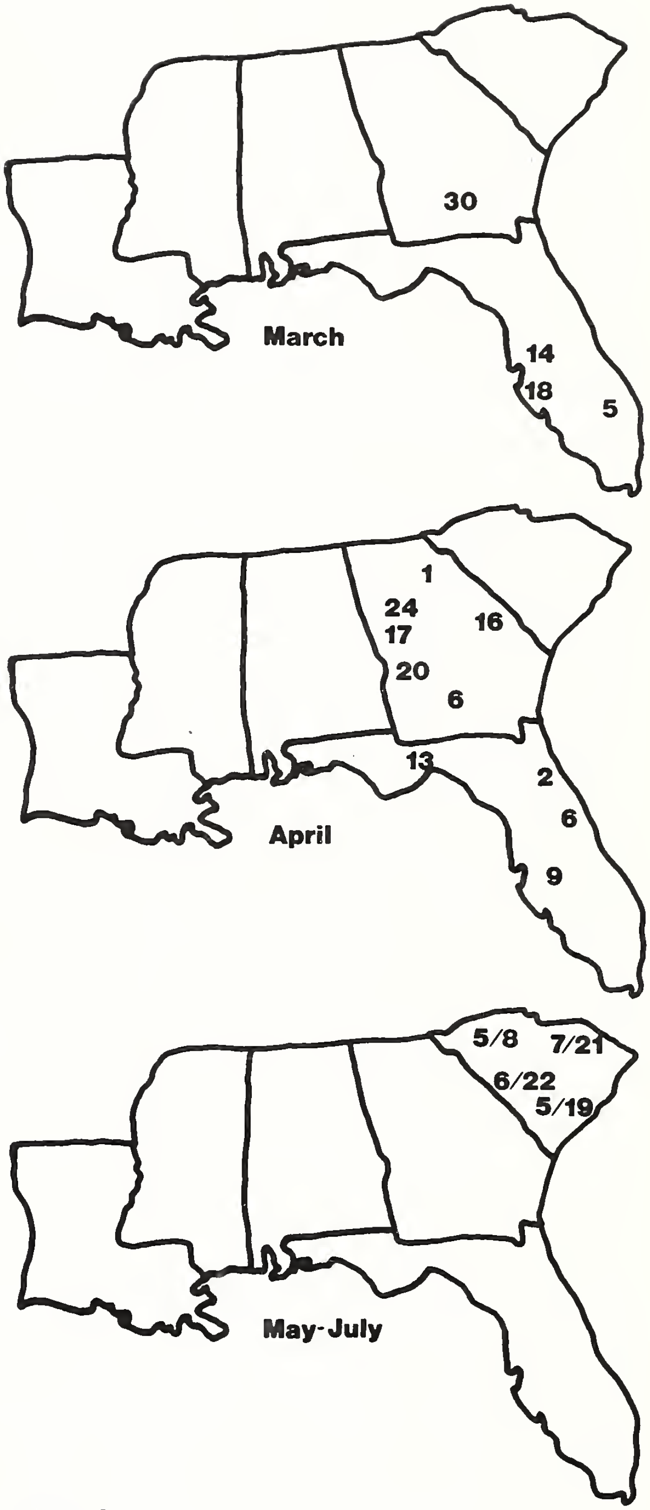

Figure 2
First occurrence of FAW males in pheromone traps, by date, 1981.

The progression of FAW larval populations during the spring of 1981 is shown in figure 3. Infestation levels in south Florida during March reflected the restraints placed on FAW populations by subfreezing temperatures, which severely limited the availability of host plants. High FAW populations were observed only in Dade County, FL, mainly on volunteer corn. Commercial seed corn is grown extensively in this area, and harvest waste provides the seed sources for growth of volunteer cornfields. Some fields were about 50 ha in size, contained up to 88,000 corn plants/ha, and were 100 percent infested. Later, low-level infestations appeared in central Florida during April. By early June, FAW infestations of varying intensity were recorded throughout the five-State area that was surveyed. Particularly heavy infestations were observed in both the southern and Panhandle areas of Florida, and light infestations of varying intensity were recorded in other areas along the Gulf Coast, extending to Louisiana.

Figure 3
Relative infestation levels of FAW on corn or sorghum, 1981. 0=no detection, 1=1-5 percent, 2=6-25 percent, 3=26-50 percent, 4=51-75 percent, and 5=76-100 percent.

Spring Movement, 1982

Weather conditions similar to those in 1981 were also observed in January 1982. However, after the freezes that occurred throughout most of Florida, the temperature quickly warmed and remained above the norm for the rest of the spring. The warmer conditions apparently allowed FAW populations to develop much more rapidly than they did in 1981. FAW males were detected in Georgia and South Carolina more than 1 month earlier than in 1981 (fig. 4). Many of the first trap captures of FAW at different locations during the spring of 1982 occurred in distinct periods. For example, of the dates recorded during January through April, catches can be grouped into rather discrete periods, one each in January and February and two in March. The synchrony of catches during April through June is less evident, probably because of the

Figure 4
First occurrence of FAW males in pheromone traps, by date, 1982.

increased number of sites from which adults could have emerged.

Larval infestations of FAW detected in corn during 1982 are shown in figure 5. As in 1981, the heaviest infestations in 1982 were again recorded in southernmost Florida from February to April and gradually intensified and progressed throughout peninsular Florida until corn in other States also became infested. During June and July, scattered heavy infestations had appeared in Georgia and South Carolina. Although no surveys were conducted during June and July in Alabama or other Gulf Coast States, infestations there were reported as light. Drought conditions prevailed over wide areas in the Southeast during spring and may have contributed to a decline in FAW populations in those

Figure 5
Relative infestation levels of FAW on corn or sorghum, 1982. 0=no detection, 1=1-5 percent, 2=6-25 percent, 3=26-50 percent, 4=51-75 percent, and 5=76-100 percent.

areas. During May in parts of north Florida, south Georgia, and Alabama, many unirrigated cornfields had sparse plant stands and were subjected to extreme drought stress.

These data suggest that a progression of FAW from south Florida to more northerly areas occurred in 1981-82 and are probably representative of the trends to be expected in most years. As infestations become established throughout the Southeastern States, where vast acreages of various hosts are available during the summer, the potential for explosive populations of FAW increases--especially when regulating mechanisms are either disrupted or not present. When all factors are favorable for FAW development, most likely it is from these areas of the Southeast that large populations of the FAW build up and move into the Atlantic seaboard and Midwest to devastate crops in the fall.

Movement, Weather, and Outbreaks

Historical as well as current data indicate that the FAW annually migrates from overwintering areas to invade crops in more northerly regions. The extent and magnitude of movement depends on many factors, including weather. Detailed descriptions of weather-related phenomena are discussed in other papers of this proceedings. So we need only address it very briefly here. Evidence from radar sightings of insects aloft, in conjunction with meteorological soundings, suggests that most airborne insect species are oriented or displaced downwind. Furthermore, insects may be transported on frontal systems and concentrated by convergent winds into faraway areas (Greenbank 1957, Wellington 1979, and Rainey 1979).

Migratory flights from point sources of the African armyworm, *Spodoptera exempta* (Walker), have been documented in Kenya (Riley et al. 1981). These en masse flights of *S. exempta* took place shortly after sunset from emergence sites in grasslands, and migrating moths, flying downwind at heights of up to several hundred meters for at least several kilometers, were detected by radar. Similarly, we have observed radar plumes of the FAW migrating from a sorghum field on successive nights at Tifton, GA (unpublished data). Their flight behavior was similar to that reported for the African armyworm.

Weather systems that could transport insects northward over long distances from overwintering areas in Florida occur at frequent intervals during the spring of each year (Muller 1979). Of these weather types, three (Gulf Return, Coastal Return, and Frontal Gulf Return) have southerly wind components associated with them that are thought to be ideally suited for the northward transport of insects. We have observed the capture of FAW males just before interfrontal periods and shortly after the passage of such frontal systems. The influences of such fronts, when slowed or stalled, may last for several days. For example, light-to-strong southerly winds persisted in the Southeastern States for almost all of March 1982 and in two fairly distinct periods from about the 2d to the 7th and from the 12th to the 21st. During these two periods, catches of FAW males were recorded on 11 occasions at different locations in Georgia, Alabama, and South Carolina. Of these, nine (82 percent) occurred within the two intervals previously mentioned.

Most attention to the economic impact and migration of the FAW is focused mainly on the years when serious outbreaks occur. Movement undoubtedly occurs in "off" years, but when population density is so low, the movement and distances traveled are difficult to measure or detect. Except where geological formations prohibit the advance of migrants, or where extreme convergence and fallout of airborne moths occur, there is little chance that the newly invaded areas are

demarcated within very restricted limits. For instance, inherent fitness of individuals and the time of takeoff with respect to differing points of origin may determine the distance traveled and result in skewed distribution patterns.

When a severe outbreak of the FAW such as that of 1977 occurs, adult movement and the resulting larval infestations are more dramatic. Most often, it is during severe outbreak years that the term "migratory" is applied to the FAW. However, some type of local or long-range dispersal for the purpose of feeding, mating, or oviposition, etc., probably takes place nightly during the lifespan of an individual adult. The elements of dispersal must certainly occur with similar frequency and at similar distances from year to year, but they may be less apparent because of the lower population densities involved. In addition, local meteorological events, such as low-level jets (which may go undetected or unmeasured by standard weather observations), may greatly influence the dispersal behavior of FAW, in both direction and the overall distances attained. The characteristics of weather at the local level may well determine whether areas with new host plants are invaded en masse by FAW or whether the FAW are transported to less favorable habitats. The difference in "boom or bust" years for the FAW may well depend on such weather factors.

Acknowledgments

We thank the following persons and institutions who provided advice, monitored traps, and collected data: Van Waddill, Joan Duskey, Paul Mislevy, David Shuster, Gary Leibee, Donald Herzog, and Richard Sprenkel, University of Florida; Ron Weeks, Lathan Hooks, Ed Knowles, and Claude Pike, Alabama Extension Service; Wayne Gardner, Paul Martin, and John All, University of Georgia; David Mills, Richard McDaniel, and A.L. Stacey, Georgia Extension Service; David Alverson and Mike Sullivan, Clemson University; Augustine Day and Steve Roach, U.S. Department of Agriculture, Agricultural Research Service; George Wilson Flying Service, Alabama; and Dean Remick of A. Duda and Sons, Florida.

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CIRCUMSTANTIAL ECOLOGICAL EVIDENCE FOR *HELIOTHIS VIRESCENS* MIGRATION INTO THE LOWER RIO GRANDE VALLEY OF TEXAS FROM NORTHEASTERN MEXICO

J.R. Raulston and J.E. Houghtaling[1]

Abstract

Trap-capture and wild-host-plant studies suggest that significant populations of the tobacco budworm, *Heliothis virescens* (F.), occur in the spring and fall in northeastern Mexico. Populations in northern Mexico in the spring before cotton production in the lower Rio Grande Valley and during the period of peak emergence from diapause are about one-third those observed in the Valley. Further, fall populations in northeastern Mexico are equivalent to those of the Valley. Large wild host-plant reservoirs in the central and southern regions of the State of Tamaulipas, Mexico, and the presence of favorable aerial transport mechanisms in the spring, suggest movement of these populations into the lower Rio Grande Valley.

Introduction

The tobacco budworm (TBW), *Heliothis virescens* (F.), is a pervasive, New World pest occurring throughout the Southern and Western United States, Mexico, Central America, parts of South America, and the Caribbean islands. The insect has a wide range of both cultivated and wild hosts (Barber 1937, Graham and Robertson 1970, Graham et al. 1972, Snow et al. 1974, Gross et al. 1975, Stadelbacher 1979, Hallman 1980, and Eger et al. 1982) and is considered one of the most serious pests of cotton in the United States.

Much of the current impetus in insect control is aimed at reducing our dependence on pesticides and their negative side effects. Knipling (1978) discusses the principles for a wide array of insect suppression technologies and provides a theoretical approach to management of *Heliothis* spp. populations in entire ecosystems. Implementation of many of the theories and techniques discussed by Knipling will require a good basic knowledge of the variables that affect the population dynamics of *Heliothis* spp., especially those relating to production of populations on noncultivated hosts and the possible effects of both trivial and long-range movement. Indeed, the potential capability for long-range displacement of the tobacco budworm has been shown or alluded to by several investigators (Lukefahr 1970, Hendricks et al. 1973, Haile et al. 1975, Raulston 1979, and Raulston et al. 1982).

To further our knowledge of the variables affecting TBW population dynamics, we began studies to determine if ecological evidence of movement between the lower Rio Grande Valley (LRGV) and northeastern Mexico existed and, if so, the possible impact of such movement.

Study Region

Figure 1 depicts our study region, including the LRGV of Texas, which extends west from the Gulf of Mexico about 200 km and north from the Rio Grande River about 75 km. Also shown is the State of Tamaulipas, Mexico, including the areas of our observations, which extend south from the Rio Grande River about 370 km to Tampico. In the southern region of the State, our observation area is bounded to the west by the Sierra Madre Oriental Range and to the east by the Gulf of Mexico, a distance of about 200 km. As Lukefahr (1970) observed, the Sierra Madre Oriental Range provides a natural corridor along the Gulf Coast of Mexico that could direct movement of insects.

Most of the area under consideration is included in that region described by Correll and Johnston (1970) as the

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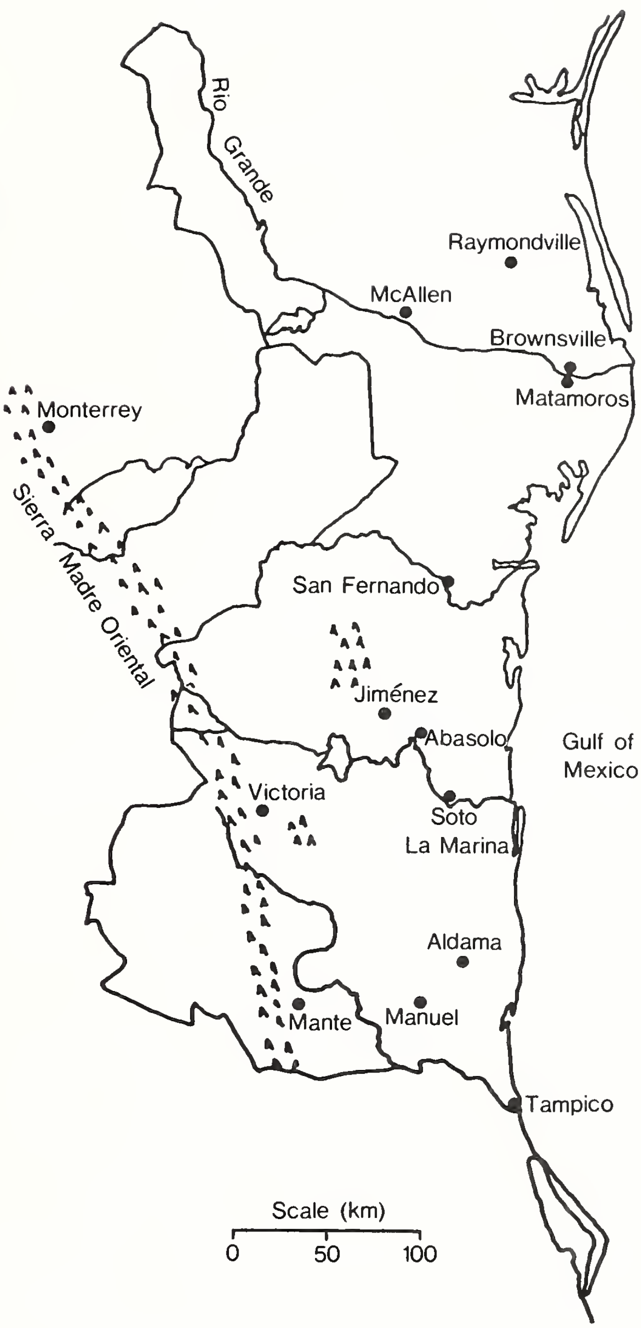

Figure 1
Map of the lower Rio Grande Valley of Texas and the State of Tamaulipas, Mexico

Tamaulipan brushlands. The LRGV (15,000 km^2) is an area of intensive agriculture with less than 5 percent remaining as native climax vegetation. Table 1 lists the major crops of the area, their approximate size, and their planting and harvesting times. Cotton is the major cultivated host of the TBW in the area. *Heliothis* spp., including the TBW, are occasionally observed in the fall and spring on some vegetables, such as bell pepper and cantaloup; however, because of the limited acreages, these vegetable crops are not important in the maintenance of TBW populations. Further, although relatively large numbers of TBW may be found in both fall and spring on tomatoes, the limited acreage of this crop would appear to make its role of little consequence in the production of TBW populations.

Northern Tamaulipas south to San Fernando is also an area of intensive agriculture (table 2), with a total sorghum production of 500,000 ha and corn production of 175,000 ha. As in the LRGV, most of the native vegetation has been removed for agricultural use.

The central region of the State (south of San Fernando to below Victoria on the west and to Aldama on the east) produces about 60,000 ha of sorghum and 80,000 ha of corn. This area is used primarily as rangeland; however, it is now in a state of ecological flux, with large areas of the native vegetation being cleared for more efficient cattle production and other agricultural use.

Planting of crops in the southern region mainly coincides with the rains occurring in June and July. Soybeans (100,000 ha), sugarcane (26,000 ha), and safflower (10,000 ha) are the three major crops in the area. Normally, a limited area of cotton is grown in the Mante area (about 1,000 ha); however, this crop is not as important to TBW production as it was in the 1960's when up to 200,000 ha were

Table 1. Crop production sequence in the lower Rio Grande Valley of Texas

Crop	Approximate area (ha)	Time of planting	Time of harvest
Sorghum	200,000	Late February	July
Cotton	120,000	Late Feb.-Early March	August
Citrus	30,000	Perennial	Fall-Winter
Corn	20,235	Late February	July
Onion	6,000	Fall	February-March
Cabbage	6,000	August	March
Melons	6,500	January	April-May
Carrots	4,000	Fall	March
Cucumber	2,500	Fall	April
Tomato	650	Spring-Fall	January-June

grown. Indeed, Lukefahr (1970) pointed out that inability to control TBW was the major factor in the demise of the cotton industry in this area.

Climate

The LRGV and much of the State of Tamaulipas is classified as semiarid. Normally, the rainfall is poorly distributed and comes in the form of thunderstorm activity. Precipitation maximums normally occur in September, with smaller peaks occurring in May and June (fig. 2). Average precipitation in the region for 3 or 4 years (1979-81) ranged from 760 mm at Abasolo (central Tamaulipas) to 680 mm in the LRGV. Cuauhtemoc (about 20 km east of Manuel) averaged 710 mm for the 4 years. The 40-year average precipitation at Brownsville, TX (1940-80), was 681 mm.

Average temperatures at Brownsville for the winter months of November-February were 3°-5°C lower than those observed in the central or southern regions of Tamaulipas (fig. 3). Further, temperatures at Abasolo were higher throughout the year than those at either Brownsville or Cuauhtemoc.

Since windflow systems that provide aerial-transport mechanisms are covered in detail in two papers elsewhere in this book ("Climatic Opportunities for the Long-Range Migration of Moths" and "Relationship Between Radar Entomological Measurements and Atmospheric Structure in South Texas During March and April 1982"), the subject will not be addressed here. However, Raulston et al. (1982) reported

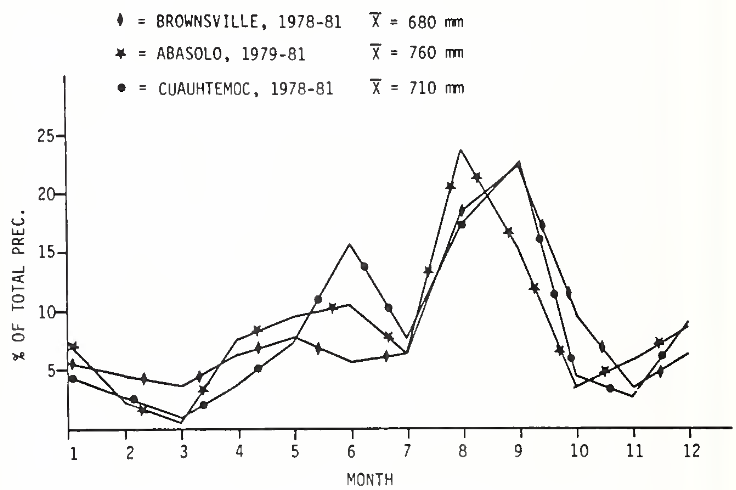

Figure 2
Three-or 4-year average monthly precipitation for Brownsville (lower Rio Grande Valley), Abasolo (central Tamaulipas), and Cuauhtemoc (southern Tamaulipas).

Table 2. Crop production sequence in the State of Tamaulipas, Mexico

Crop	Approximate area (ha)	Time of planting
Northern area		
Sorghum	140,000 (irr.)	February
	300,000 (dry)	February
	10,000 (irr.)	July
	50,000 (dry)	July
Total	500,000	
Corn	120,000 (irr.)	February
	5,000 (dry)	February
	40,000 (irr.)	July
	10,000 (dry)	July
Total	175,000	
Beans	20,000 (irr.)	August
Central area		
Sorghum	30,000 (irr.)	February
	15,000 (dry)	February
	10,000 (irr.)	July
	5,000 (dry)	July
Total	60,000	
Corn	20,000 (irr.)	February
	30,000 (dry)	February
	10,000 (irr.)	July
	20,000 (dry)	July
Total	80,000	
Beans	10,000 (irr.)	August
Southern area		
Sorghum	2,000 (dry)	May
Soy	100,000 (dry)	June-July
Safflower	10,000	November
Tomato	<500	Sept.-Oct.
Onion	<500	Sept.-Oct.
Chili peppers	1,000	July-Oct.
Sugarcane	26,000	
Corn	<5,000	Variable
Cotton	1,000	June-July

that systems develop in this region during the months of March-May that could transport insect populations in a northerly direction.

Spring Population Dynamics

The LRGV is the only area in our study region that produces a major cultivated host (cotton) of the TBW. Most of this cotton is planted between days 50 and 70 and normally begins squaring around day 120. Although TBW oviposition occurs on cotton before fruiting, mortality factors (host phenology, predation, parasitism) apparently eliminate these insects. Therefore, the first spring TBW trap-capture peaks at Brownsville, shown in figure 4 for 1978-80, are produced from other hosts or migrate into the

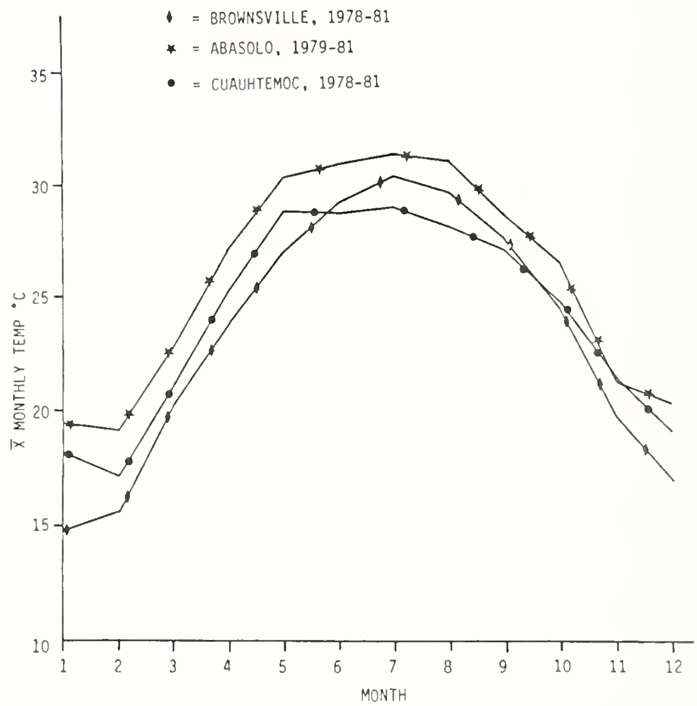

Figure 3
Three-or 4-year average monthly temperatures for Brownsville (lower Rio Grande Valley), Abasolo (central Tamaulipas), and Cuauhtemoc (southern Tamaulipas).

area. Also shown in figure 4 is the 4-year average TBW trap capture at San Fernando, Mexico. The San Fernando area produces no major cultivated TBW hosts, and trap captures here indicate a population developing as a result of naturally occurring ecological conditions. The spring trap-capture peak at San Fernando occurred between days 70 and 100 and accounted for 33.8 percent of the yearly total for an average capture per trap of 159 for the 30-day period. During the same 30 days, 5.8 percent (418/trap) of the yearly total at Brownsville was captured. Interestingly, 70 percent of the TBW emergence from diapause at Brownsville occurs during this period (fig. 5).

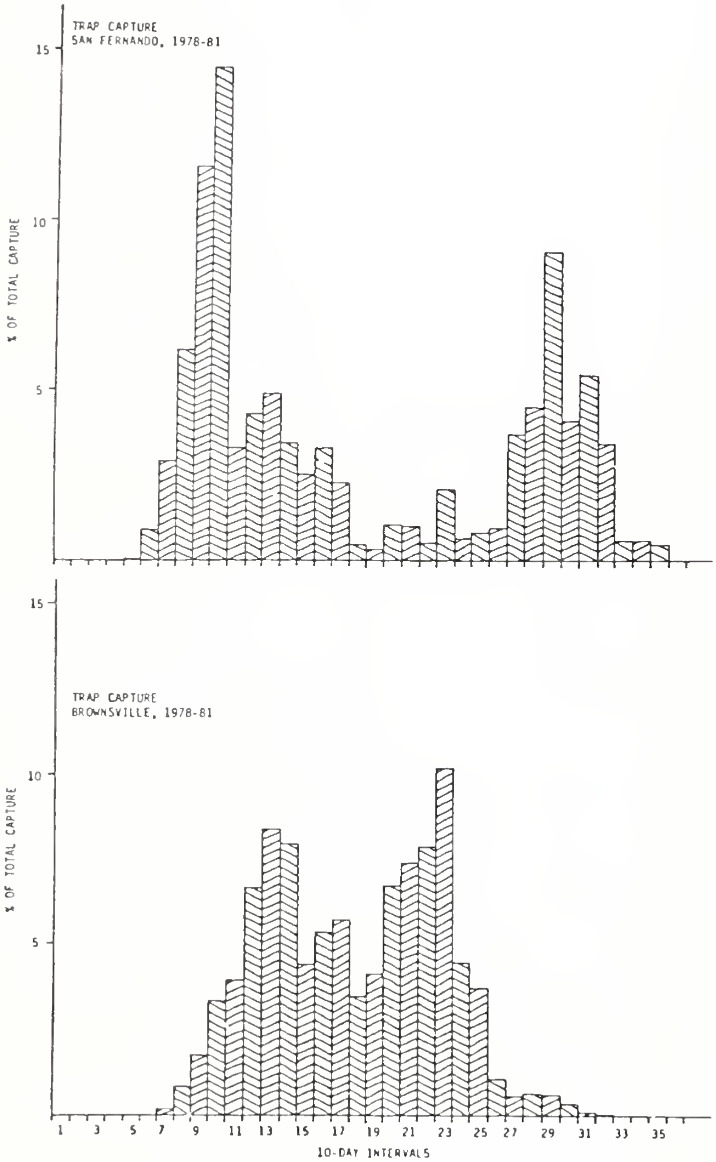

Figure 4
Four-year average tobacco budworm capture in traps located at San Fernando, Mexico (4 traps), and Brownsville, TX (10-25 traps).

The diapause induction data (fig. 6) and emergence data (fig. 5) are obtained from locally occurring wild populations. In the fall and winter, larvae are collected from cultivated host plants (cotton and pigeon peas) and wild host plants for these studies. Collected larvae are placed on an artificial diet (Shaver and Raulston 1971) in 14-g plastic cups. The larvae are held outside in a shaded area, and their date of pupation is recorded. Later, the pupae are observed 5-10 days past pupation for larval eyespots to determine their condition (diapausing or nondiapausing). Those pupae retaining the larval eyespots are then placed in a 1.8-cm plastic tube fitted on one end with a cotton plug and on the other end with a 113-g plastic cup covered with a fine mesh plastic screen to facilitate air transfer. The plastic tube is inserted in the ground to a depth where the pupae will be 2.5-5.0 cm below the surface. Emerging adults climb the tube and are contained in the cup, which is above ground where their emergence can be observed and recorded.

The trap data (fig. 4) indicate that the TBW population in the San Fernando area is 0.38 of that occurring in the Brownsville area during the diapause emergence peak. Trap capture in the San Fernando area declines rapidly after day 100 but continues to increase at Brownsville to about day 140.

TBW larvae are often observed in the spring in the San Fernando area on <u>Nicotiana rapanda</u> (Willd.), <u>Abutilon</u>

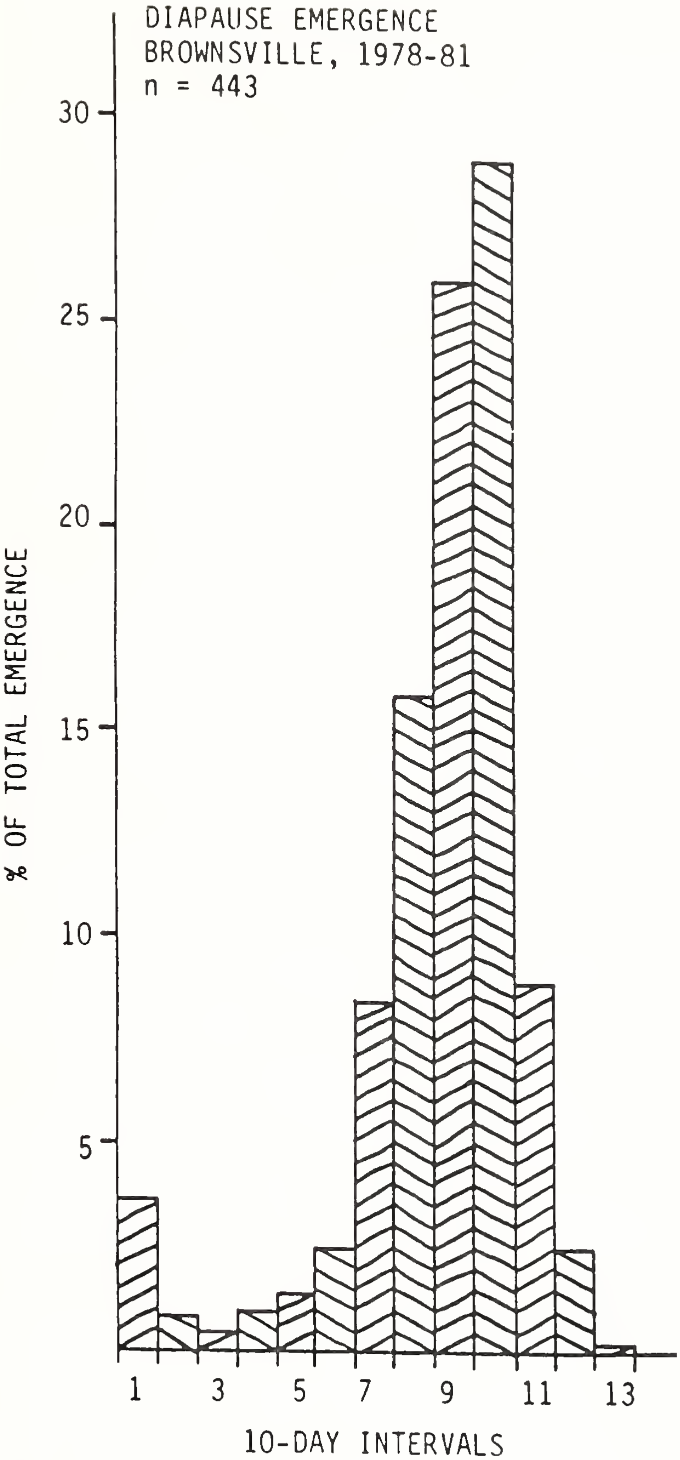

Figure 5
Emergence from diapause of tobacco budworm at Brownsville, TX. Data are averaged over 4 years (1978-81).

trisulcatum (Jacq.), and Bastardia viscosa (L.), a plant reported by Snow et al. (1974) as the major TBW host on St. Croix, U.S. Virgin Islands. Indeed, in 1981 a 54-ha area was observed near San Fernando that had been cleared of native vegetation and was maintaining a dense stand of B. viscosa. A survey of this field indicated a plant density of 17,944/ha. Heliothis spp. larval collections were begun in the

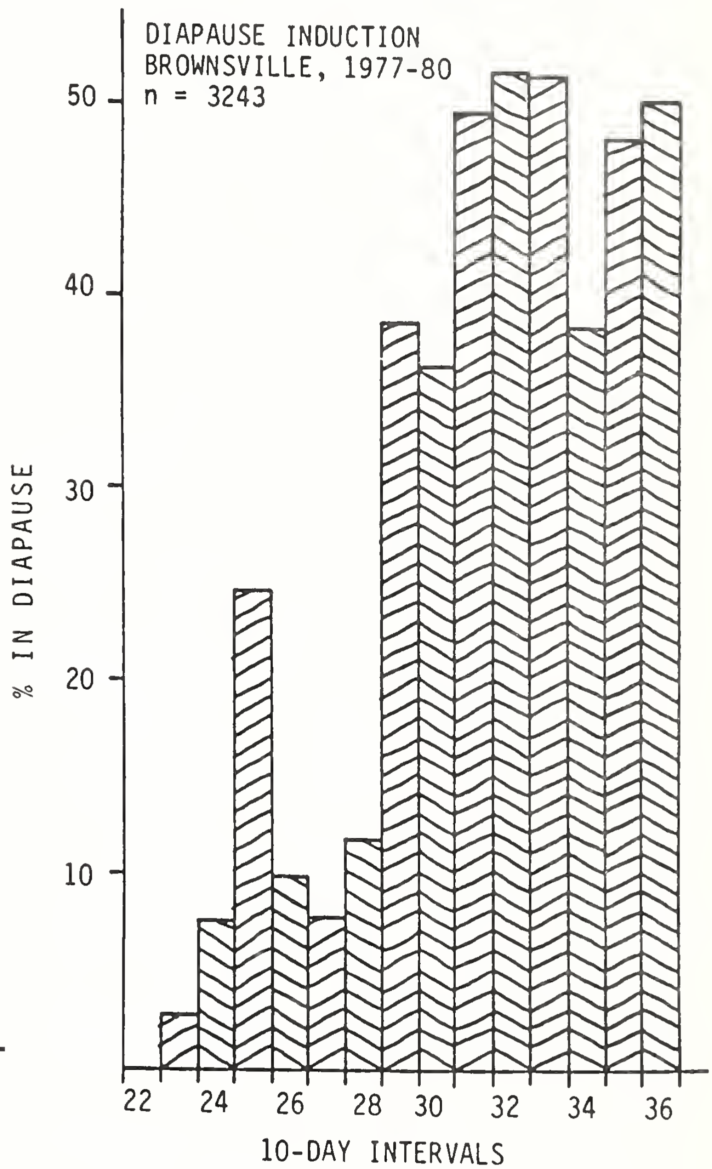

Figure 6
Tobacco budworm diapause induction at Brownsville, TX (1977-80).

Table 3. Occurrence of tobacco budworm larvae on <u>Bastardia viscosa</u> near San Fernando, Mexico, 1981[1]

Julian day	Number per plant	Percent of larvae: Small	Percent of larvae: Medium	Percent of larvae: Large	Percent parasitized	Estimated[2] number of larvae/ha
77	0.15	85.0	5.0	10.0	20.0	2,691.7
84	.12	68.0	10.5	21.0	10.5	2,153.3
93	.54	64.7	31.4	3.9	5.9	9,690.0
98	.13	29.2	50.0	20.8	8.3	2,332.8
105	.02	0	100	0	0	358.9
147	.86	48.8	44.2	7.0	4.7	15,432.2
154	.10	0	0	100	20	1,794.4
174	.02	100	0	0	0	358.9
266	.08	50	50	0	0	1,435.6
280	.02	100	0	0	0	358.9

[1] No larvae were found on Julian days 64, 70, 182, 195, 209, 224, 238, 246, and 257.

[2] Estimated from 50 plant samples/observation day.

field on day 64 and continued to day 280. On each collection day, larval counts were made on 50 plants, and results (table 3) indicate an initial TBW larval peak of about 10,000/ha on day 93. This larval peak also corresponded with the diapause emergence peak observed in Brownsville (fig. 5). A later peak of over 15,000/ha occurred on day 147; afterwards the plants senesced because of lack of precipitation and became unattractive as hosts for the rest of the summer. <u>Heliothis zea</u> (Boddie) larvae were also present on the <u>Bastardia</u> at about the same frequency as TBW.

We have observed that both <u>B. viscosa</u> and <u>A. trisulcatum</u> are very prevalent in central and southern Tamaulipas along roadsides and in fallow fields. Further, in those areas that are being cleared of native vegetation, one or both of the species appears in dense stands similar to that observed in the field near San Fernando. Those areas that are later used as rangeland retain these dense stands because of their unpalatability to livestock. Although at the present we do not know how large these plant populations are, they could be tremendous reservoirs for <u>Heliothis</u> spp. production in the spring.

Graham and Robertson (1970) and Graham et al. (1972) discuss the wild host plants in the LRGV and suggest that <u>N. rapanda</u> is the most important wild host in the LRGV for TBW reproduction in the spring. We conducted host-plant surveys including <u>N. rapanda</u>, <u>B. viscosa</u>, and <u>A. trisulcatum</u> in Cameron County, TX (Brownsville area), in 1979-80 (November-January) and 1981

Table 4. Survey of tobacco budworm wild host plants in Cameron County, TX

Plant species	Average plants/surveyed ha in--	
	1979-80[1]	1981[2]
Nicotiana rapanda	3.8	2.7
Bastardia viscosa	1.5	1.4
Abutilon trisulcatum	.3	2.5

[1] Area surveyed = 15,082 ha; 73 plots in a 282,727-ha area.

[2] Area surveyed = 2,486 ha; 14 plots in a 54,222-ha area.

(March-April). The surveys were conducted by selecting plots (28-511 ha in size) from aerial photographs of the county (Williams et al. 1977). A total of 73 plots (15,082 ha) dispersed countywide were observed in 1979-80 while 14 plots (2,486 ha), located mainly along the Rio Grande River, were observed in 1981. These surveys indicated that more *N. rapanda* (68 percent in 1979-80 and 40 percent in 1981) than *B. viscosa* and *A. trisulcatum* were growing in these plots (table 4). Plant populations were extremely variable between examination plots. Indeed, 66 percent of the *N. rapanda* observed in the 1979-80 survey was observed in one survey plot that contained about 3 ha of a dense stand of this species. The extreme variability in host-plant populations is further illustrated by one area not in our survey plots. This area (34 ha) had been cleared of brush in 1979 for a housing development project and was supporting plant populations in March 1981 of: *N. rapanda*, 6,150/ha; *B. viscosa*, 18,448/ha; *A. trisulcatum*, 1,822/ha. Graham et al. (1970) also pointed out the difficulty of assessing the role of wild hosts in the LRGV because of the variation in their density.

Of course, the data are subject to large experimental error, but a projection of the average plant populations observed in our 2 surveys over the entire LRGV (total area = 1.5 million ha) gives minimum plant populations of the following sizes: *N. rapanda*, 4.9 million; *B. viscosa*, 2.2 million; *A. trisulcatum*, 2.1 million. Areas such as the 34-ha area described previously may influence these populations; however, considering that most of the native vegetation has already been removed from the LRGV, such areas would probably play a relatively minor role. Further, major plant population fluctuations occur as a result of fluctuations in precipitation over several years.

Data in table 5 show TBW infestations on *N. rapanda* for 1978-81. Oviposition peaks normally occurred within the 30-day period of peak emergence from diapause shown in figure 5. Production of large TBW larvae on *N. rapanda* was low and for the 4 years, averaged 6.5/1,000 plants from day 60 to 90 and 59/1,000 plants from day 90 to 120.

Assuming the large larvae produced from day 90 to 120 yield the adult insects available to infest cotton and considering the estimated *N. rapanda* plant populations

Table 5. Incidence of tobacco budworm on N. rapanda near Brownsville, TX[1]

Julian day	No. plants observed	Avg. egg/ plant	Avg. larvae/plant		
			Small	Medium	Large
1978					
71-80	300	1.73	0.04	0.002	0
81-90	300	.92	.39	.10	.006
91-100	200	.47	.41	.13	.03
101-110	100	.50	.31	.10	.01
111-120	200	.48	.54	.20	.015
121-130	100	.19	.39	.09	0
1979					
51-60	56	0	0	0	0
61-70	245	.21	0	0	0
71-80	269	.88	.02	.01	0
81-90	270	1.08	.07	.11	.01
91-100	240	.92	.20	.18	.03
101-110	120	.46	.20	.18	.07
111-120	30	.83	.07	0	0
1980					
21-30	50	0	0	0	0
31-40	150	0	0	0	0
41-50	200	0	0	0	0
51-60	150	.05	.03	0	0
61-70	200	.07	.04	0	0
71-80	200	.09	.08	.03	.01
81-90	50	.06	.08	0	0
91-100	50	.12	.18	0	0
1981					
21-30	25	0	0	0	0
41-50	25	0	0	0	0
81-90	100	0	0	0	0
91-100	100	([2])	0	0	0
101-110	50	([2])	.14	.02	0
111-120	50	([2])	.06	0	0
121-130	50	([2])	.82	.12	.08

[1] In 1978, no plants were observed on Julian days 21-70; in 1979, no plants were observed on Julian days 21-50 and 121-130; in 1980, no plants were observed on Julian days 101-120; in 1981, no plants were observed on Julian days 31-40, 51-60, and 61-70.

[2] In 1981, plants were not checked for eggs on Julian days 91-130.

presented above, about 300,000 TBW would be produced from this plant species.

TBW infestation of early season cotton is presented in table 6. As stated previously, the prefruiting cotton does not appear to increase the TBW population since no large larvae are observed even though eggs and small- to medium-sized larvae are present. Initial oviposition peaks occurred between days 100 and 130, and it is apparent that the cotton crop did not produce the adults responsible for this peak. The size of the initial peaks was extremely variable and ranged from 115,912 eggs/ha (1978) to 3,034 eggs/ha (1980). The situation observed in 1978 occurs periodically in the LRGV and may be a result of a major migration. This heavy infestation was widespread over the LRGV (John W. Norman, personal communication) and inflicted heavy early season damage on the cotton. If we assume the average fecundity of a TBW female to be 1,000 eggs, this peak required the total egg production of 115 females/ha or, projecting over the entire cotton crop (120,000 ha), a total moth population (male and female) of 27.6 million. Even considering that this figure is subject to large experimental error due to field-to-field variation, the production of such a large population is certainly beyond the capacity of the wild host-plant populations within the area.

Fall and Winter Population Dynamics

Graham et al. (1972) showed that during its fruiting period, cotton was the principal host of TBW in the LRGV. However, the LRGV cotton growers are required by law to plow their fields by day 243. Thus, the principal host is destroyed before induction of diapause and is unavailable for production of overwintering populations. Indeed, removal of cotton as a host plant results in the TBW trap-capture decrease at Brownsville, TX, after day 234, as shown in figure 4.

Table 6. Tobacco budworm infestation on cotton in the Brownsville area for 1978-81; 1 to 6 fields were checked on each observation date

Day	Average eggs/ha	Average larvae/ha		
		Small	Medium	Large
1978				
110	551	0	0	0
114	8,854	553	553	0
117	15,493	2,763	0	0
121	115;912	5,426	603	0
124	42,953	16,884	0	0
129	20,662	2,580	0	0
132	16,143	1,841	460	0
136	16,143	0	0	0
139	4,519	0	0	0
1979				
96	1,378	0	0	0
104	2,345	551	0	0
110	2,483	475	0	0
113	10,764	0	0	0
123	15,632	0	0	0
128	15,678	10,769	1,922	0
131	9,521	3,311	2,071	0
136	415	4,554	415	0
142	1,656	3,726	415	0
1980				
102	3,034	0	0	0
107	1,932	276	0	0
115	828	0	0	0
119	551	0	0	0
125	551	276	0	0
132	0	2,483	0	0
140	276	276	0	0
147	828	551	0	0
1981				
107	52,419	0	0	0
112	17,660	1,932	0	0
118	14,623	551	828	0
125	276	551	278	0
131	3,588	551	1,379	0
135	3,862	1,105	1,379	0
138	828	551	0	0
142	1,838	1,656	551	551
146	2,898	1,379	551	0
149	1,656	551	551	1,105

Although low levels of diapausing pupae were observed at Brownsville earlier, the peak does not occur until after day 280 (fig. 6). TBW trap capture at San Fernando exhibits a second peak (day 270-320) during the time of major diapause induction. During this 50-day period, 24.3 percent (114/trap) of the yearly total was captured compared with 1.8 percent (132/trap) at Brownsville. So during the diapause induction period, TBW populations in the LRGV and northeastern Mexico are roughly equivalent.

The origin of the fall population at San Fernando is not known; however, windflow patterns taken from pseudoadiabatic charts at Brownsville (table 7) in 1979 show that a southerly flow between 340° and 20°, which would transport moths into the San Fernando area from south Texas, occurred on 38 percent of the days at or below 1,500 m between days 270 and 320. In view of the hot and very dry period experienced in the region during the summer months, another possible source of developing fall populations may be emergence from insects quiescing as pupae through the summer as suggested by George Butler and Peter Lingren (personal communication). Although no data from the area are available concerning this phenomenon, research into this possibility should be considered.

Graham et al. (1972) further showed that during the peak diapause induction period, A. trisulcatum was the major wild host in the LRGV. From four surveys made between days 300 and 334, he observed an average of 0.11 TBW larvae/plant on this species. In 1981, examinations of A. trisulcatum and B. viscosa in the Brownsville area between days 204 and 337 yielded no TBW larvae before day 279. Larval counts between days 279 and 289 ranged from 0 to 0.14/plant on B. viscosa and 0.02 to 0.06/plant on A. trisulcatum. No larvae were found on either species after day 289. Fall examinations of these plants in 1982 have yielded no larvae from these species in the LRGV. Our observations as well as those of Graham et al. (1970) indicate the diapausing populations in the LRGV are relatively low.

Over the last 4 years, during sporadic trips into central and southern Tamaulipas in the fall, we have found both TBW and H. zea on A. trisulcatum and B. viscosa. In view of the abundance of these plant species in the area, in 1982 we began larval surveys on these plants to determine whether they are used as hosts for Heliothis spp. In our initial survey (days 263-266), blooming A. trisulcatum was observed in the area south of Victoria to Mante; however, no Heliothis spp. larvae were found. Also, blooming A. trisulcatum and B. viscosa were present in large populations from Manuel to north of Soto la Marina; however, again no larvae were observed. On a second trip on day 280 into the Soto la Marina area, we again found no Heliothis spp. on these plants. A. trisulcatum examined on day 292 at the Cuesta de Llera (about 50 km south of Victoria) had an average infestation of 0.05 larvae/plant; 29 percent were TBW. Collections made at Aldama on day 294 indicated an infestation rate (A. trisulcatum and B. viscosa mixed) of 0.42 larvae/plant (26 percent TBW). Between days 319 and 321, no larvae were found on plants at the Cuesta de Llera as the plants had senesced; however, examination of A. trisulcatum at El Gueylo, about 20 km south, indicated an infestation of 0.04/plant (species not determined). Also, A. trisulcatum at Gonzalez was infested at a rate of 0.12 larvae/plant (75 percent TBW) and at Aldama at a rate of 0.08 larvae/plant (93 percent TBW). These preliminary data, as well as observations made in previous years, suggest that this area and these two plant species may act as important reservoirs for TBW populations in the fall as well as in the spring.

Table 7. Altitudes and temperatures at which a wind direction between 340° and 20° was observed from radiosondes at Brownsville, TX, in 1979[1]

Day	September		October		November	
	Altitude (X1,000)	Average temp. (°C)	Altitude (X1,000)	Average temp. (°C)	Altitude (X1,000)	Average temp. (°C)
1			6-9	13.3	0,5	12.2
2			6-9	12.8	0-1,4	21.1
3					5-9	8.3
4	6-9	12.8			7	6.1
5			6-7	12.8		
6			6-9	14.4	3-4	16.1
7			8-9	12.2		
8						
9	0-1	23.9				
10	9	9.4	7-9	12.2	0	26.1
11	1-8	16.7			1,4,6	11.1
12	1-9	15.0	8-9	13.9	2-4	11.1
13	2-9	15.6			0-6	11.7
14	0-9	18.9			0-8	9.4
15	0-8	18.9				
16	0-7	16.1	9-10	13.3		
17	0-4	19.4	9	11.1		
18	0-4	20.0				
19						
20	2-9	25.0				
21	5-10	12.2	9	13.9		
22	4-10	13.9			0-1,4	13.3
23	7-9	11.1	0-6	14.4	0-5	7.2
24	2-7	16.7	0-6	13.9		
25	4-8	11.7	0,4-5	13.9	2-3	12.8
26	0-6	20.6	9	11.1		
27	0-4	21.1				
28	3-9	13.3			0-2	16.7
29	5,7	15.0			0-6	5.0
30					0-6	5.0

[1] Hyphen between altitudes indicates continuous readings between 340° and 20°; comma indicates missing data between altitudes.

Conclusions

Data presented here suggest that significant populations of TBW occur in noncultivated host areas in the State of Tamaulipas, Mexico, before and after the cotton crop grown in the LRGV. Spring populations as indexed by trap capture at San Fernando for a 4-year period were one-third the size of those observed in the LRGV; fall populations were equivalent. In view of the size of the wild host reservoir available in central and southern Tamaulipas, the capacity of the area to produce TBW in spring and fall far exceeds that of the LRGV. In early season, it appears that these hosts are available only for a limited time because of rapid senescence brought on by the lack of precipitation. Habitat deterioration would make emerging populations available for migration as discussed by Hughes (1979). Then, considering the wind patterns observed within the area by Raulston et al. (1982), aerial transport mechanisms are available that favor movement toward the LRGV.

Certainly, our data do not prove that TBW migration occurs within this region. However, in view of the temporal sequences of the development of populations in the region, the possibility of such movement is suggested. A long-range concentrated effort will be required to provide a more accurate description of the size of TBW and host-plant populations within the total region, including the LRGV, to make definite conclusions relating to movement and importance of such movement of this insect.

Acknowledgments

We gratefully acknowledge the efforts of John W. Norman, extension agent, entomology, Texas Agricultural Extension Service, Weslaco, TX, and Jesus Loera, entomologist, Secretaria de Agricultura y Recursos Hidraulicos, Instituto Nacional de Investigaciones Agricolas, Centro de Investigaciones Agricolas del Golfo Norte, Rio Bravo, Tamaulipas, Mexico, for providing data on cropping systems in the lower Rio Grande Valley of Texas and the State of Tamaulipas, Mexico. We further thank Ing. Victor Sanchez, entomologist, Cuauhtemoc, Tamaulipas, Mexico, and Ing. M.C. Felix Pedraza Martinez, entomologist, Abasolo, Tamaulipas, Mexico, for providing weather data from their respective stations; both are with the Secretaria de Agricultura y Recursos Hidraulicos, Instituto Nacional de Investigaciones Agricolas, Centro de Investigaciones Agricolas del Golfo Norte.

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EARLY SEASON OCCURRENCE OF *HELIOTHIS* SPP. IN 1982: EVIDENCE OF LONG-RANGE MIGRATION OF *HELIOTHIS ZEA*

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Abstract

Circumstantial evidence suggests that a major migration of corn earworm, *Heliothis zea* (Boddie), adults into Texas and the lower Mississippi River Valley occurred in March of 1982. The day that the first *H. zea* moth was caught was not related to increases in temperature as expected with increases in latitude from south to north. Large increases in pheromone trap captures of moths occurred in Texas, eastern Louisiana, Arkansas, and Mississippi in March. These increases seemed to be related to the nearly continuous south to north airflow that occurred from March 11 to 20. Similar increases in moth capture did not occur in the Southeastern United States during the same period. At this time the opportunities for south to north air transport in the Southeast were considerably less than those in the areas with large moth increases. Also, during this same period, evidence was obtained to indicate that a comparable migration of *Heliothis virescens* (F.) into Texas and the lower Mississippi River Valley did not occur.

Introduction

Whether *Heliothis zea* (Boddie) (corn earworm, CEW) and *Heliothis virescens* (F.) (tobacco budworm, TBW) migrate has long been the subject of speculation. Hartstack et al. (1982) reviewed the subject of insect migration and presented circumstantial evidence that suggested that there was a major migration of CEW adults in 1981 into areas around College Station, TX, and Portland, AR. They estimated that the peak pheromone trap catch was 19 and 33 days ahead of the peak local diapause emergence at College Station and Portland, respectively. They found that excellent atmospheric opportunities for transport of CEW moths from Mexico and south Texas to central Texas and Arkansas existed during late March and April when peak catches occurred. They also found little evidence of TBW migration during this period; however, since TBW populations are much smaller than those of CEW in the source areas, the movement of TBW may be harder to detect.

Although circumstantial, the evidence for migration of CEW presented by Hartstack et al. (1982) was very strong. It was based on the fact that TBW moths emerged from diapause in cages 7 days before the CEW moths and that the pheromone trap catches of TBW moths coincided with the TBW emergence from diapause. If the technique used to monitor TBW diapause emergence delayed the emergence or was not representative of the diverse habitats where pupae may diapause, then the trap catch should not have had similar timing and peaks. Therefore, Hartstack et al. (1982) concluded that the data on emergence from diapause of the CEW moths should also be valid since there is no evidence that CEW pupae diapause in more diverse habitats than do TBW pupae.

The data presented here were collected in 1982 as an extension of the research reported by Hartstack et al. (1982). We used pheromone traps in 14 Cotton Belt States to determine the early season occurrence of *Heliothis* spp. and compared the results with environmental conditions to study *Heliothis* migration.

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Methods and Materials

Pheromone traps were operated at 50 locations across the Southern United States. Most of the traps were installed by March 1; the exceptions were due to logistical problems. At some locations, such as those in California, Arizona, and Florida, CEW moths were captured as soon as the traps were installed, indicating that moths were present before March 1. Traps were installed in mid-April in North Carolina because no moths are present in March. Figure 1a shows the location of the pheromone traps across the Cotton Belt. To standardize the monitoring system as much as possible, most traps and baits were furnished by the U.S. Department of Agriculture's Agricultural Research Service coordinators at College Station, TX; however, the traps were usually operated by local scientists, consultants, or farmers who volunteered to cooperate with this project.

Pheromone Dispensers

The dispensers used in the pheromone traps for CEW contained the four chemical components identified by Klun et al. (1979) laminated between layers of plastic (Hercon Division, Health-Chem Corp., New York, NY). An about 3.2-cm^2 piece of this formulation (1.25 mg of pheromone) was used in each trap to attract CEW. The dispensers used for TBW were the same kind of laminated plastic, containing a seven-component mixture (Klun et al. 1979) of chemicals. Baits containing the mixture were 1.6 cm^2 in size, containing about 10 mg of pheromone. Both the CEW and TBW baits were changed every 2 weeks for an assumed consistent output of attractant.

Pheromone Traps

All pheromone traps used at the locations were either the 50-25 or 75-50 cone trap described by Hartstack et al. (1979). The two numbers in the trap designation are the approximate size in centimeters of the outer and inner core openings, respectively. Both types of traps have proven to be efficient for detecting and monitoring early season populations of CEW and TBW males, with the 75-50 trap capturing about 1.5 times more of the moths attracted than the 50-25 trap. The traps were located along field borders, usually in pairs (one CEW and one TBW), near early season hosts. To minimize potential interaction between baits, the CEW and TBW traps were separated by at least 100 m.

The traps were serviced daily if possible; however, because of logistics, many were serviced less often. When traps were not checked each day, the catches were divided equally among nights of trap operation to provide continuous nightly captures for analyses. Catches in the 50-25 trap were adjusted by multiplying them by 1.5 so that more direct comparisons to the 75-50 trap could be made.

Field-Emergence Tests

In the summer of 1981, a field plot (about 2 ha) at College Station, TX, was planted with pigeon peas to attract Heliothis spp. moths for establishment of an overwintering population of diapausing pupae. Adult emergence from overwintering was monitored during the early season in 1982 by placing 48 small cages (1.8 by 2.0 by 1.8 m) and 10 large cages (5.5 by 1.8 by 1.8 m) of natural Saran screen over part of the study plot in mid-March. The areas caged were cleared of pigeon pea stalks and all vegetation and were periodically sprayed with glyphosate. The cages were checked daily, when weather permitted, for emergence of moths.

Results and Discussion

Timing of First Moth Caught

Figure 1a shows a hand-drawn contour plot of the approximate day number that the first CEW moth was captured at each location. The location of the lines was

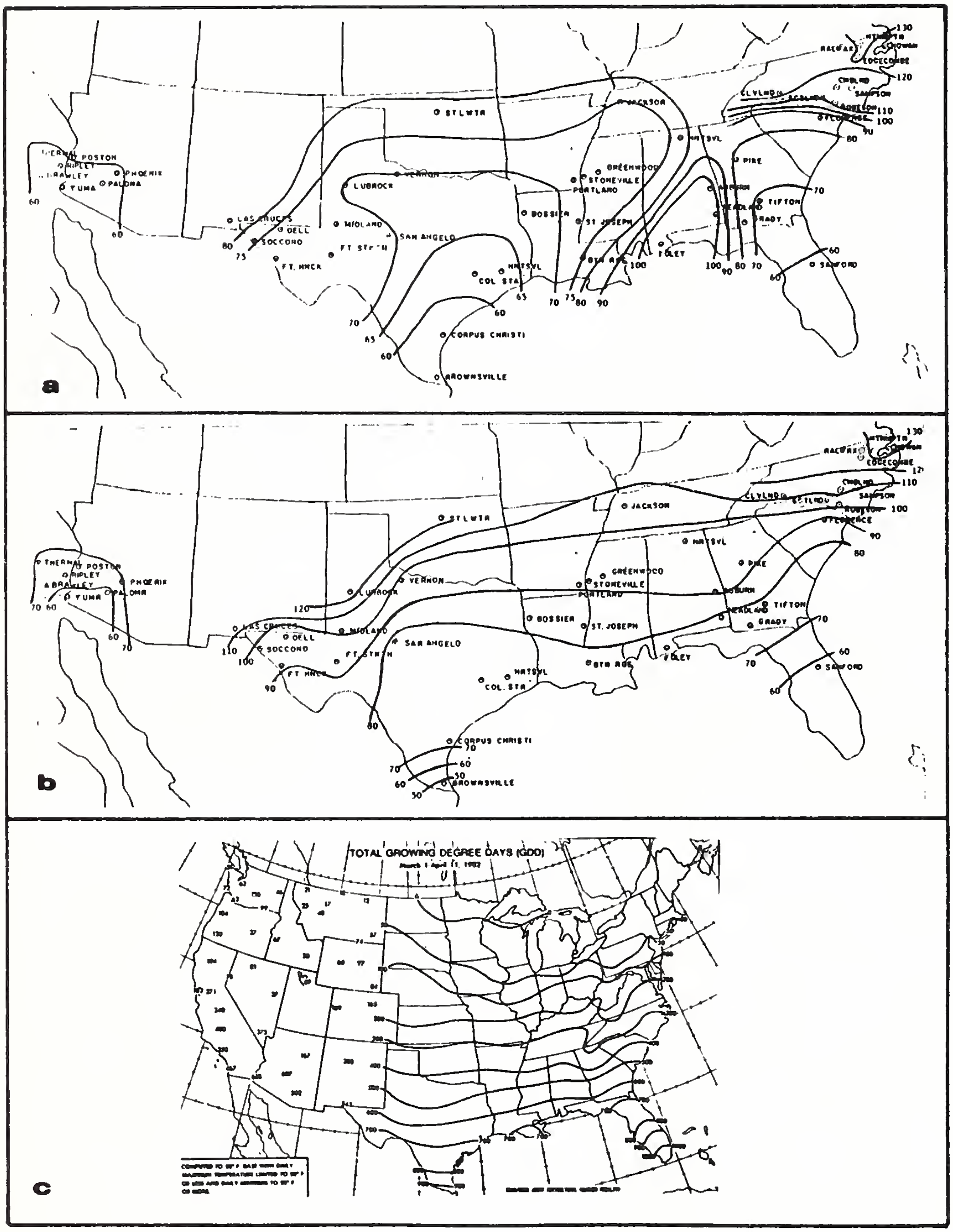

Figure 1
a, Day number that the first CEW moth was caught in 1982. b, Day number that the first TBW moth was caught in 1982.
c, Accumulated degree-days (lower and upper thresholds of 50° and 90°F from March 1 to April 11, 1982. (Reprinted from Weekly Weather and Crop Bulletin 69:15, April 13, 1982.)

estimated by interpolation between trap locations, which are shown on the figure. Figure 1b shows a similar plot for TBW moths.

The contours shown in figure 1b for TBW closely follow differences in accumulated degree-days (fig. 1c) that are expected with increases in latitude from south to north. The first TBW moth was captured 10 days later than the first CEW moth in southern Texas. However, at College Station, TX, which is farther north, the first CEW moth was captured about 15 days before TBW. At Portland, AR, Jackson, TN, Stillwater, OK, and Lubbock, TX, the first CEW moth was captured 19, 25, 25, and 50 days, respectively, before the first TBW moth. In Florida, Georgia, South Carolina, North Carolina, California, and Arizona the first TBW and CEW moths were captured at about the same time. This very noticeable difference in time of appearance had to be the result of something other than geographically related temperature differences. We believe that it was the result of CEW moth migration from Mexico or southern Texas.

During the time (March 6 to 21) when we believe that CEW was migrating, there was considerable opportunity for atmospheric transport of moths from Mexico and south Texas northward and northeastward. Very little opportunity existed, however, for transport of moths northward from Florida during this period. We will describe these wind patterns in detail later in the paper.

Looking at the CEW moth data presented in figure 1a, one can see the bulge in the contour lines from central Texas northeastward into the Mississippi Valley and then into central Tennessee. The strong southwest winds predominated in this area during this period.

Peak Number Caught

Large increases in early season trap catches of CEW occurred during the period March 11 to 21 in the central part of the trap area. Figure 2a shows the contours for the peak number of CEW moths/trap/night caught before March 11. Figure 2b shows the contours for peak number of CEW moths/trap/night caught between March 11 and March 21. The largest increases in CEW trap catch occurred from south Texas southeastward toward and up the Mississippi Valley toward Tennessee. Some increases in trap catch also occurred northward from south Texas into the Lubbock and Vernon, TX, areas. Again, in the Southeastern areas and in California and Arizona, no appreciable increase in catch of CEW occurred. Trap catches increased the most in east Texas and northwest Louisiana, particularly at Bossier City, LA, from 1 to over 200 moths/trap/night. As of March 21, no TBW moths had been captured at Bossier City.

Number Caught

Another way to look at pheromone trap catches for evidence of migration is to study the catches over time. This accumulation shows possible source areas as well as locations of migrants. Figure 3a shows the accumulated catch/trap of CEW moths through March 11. Highest accumulated catches at this time were at Yuma, AZ, with 172 moths, and Corpus Christi, TX, with 119. By March 21 (fig. 3b), accumulated catches had increased to a high of 600 moths/trap in the Corpus Christi area. The increase at Brownsville, TX, was small (22 to 126 moths/trap from March 11 to 21), while large increases in accumulated catch occurred at College Station, TX, Bossier City, LA, and Portland, AR (from 4 to 455, 0 to 400, and 0 to 136, respectively). Also by March 21, 5 moths had been caught as far north as Jackson, TN, 18 moths at Vernon, TX, and 24 at Lubbock, TX.

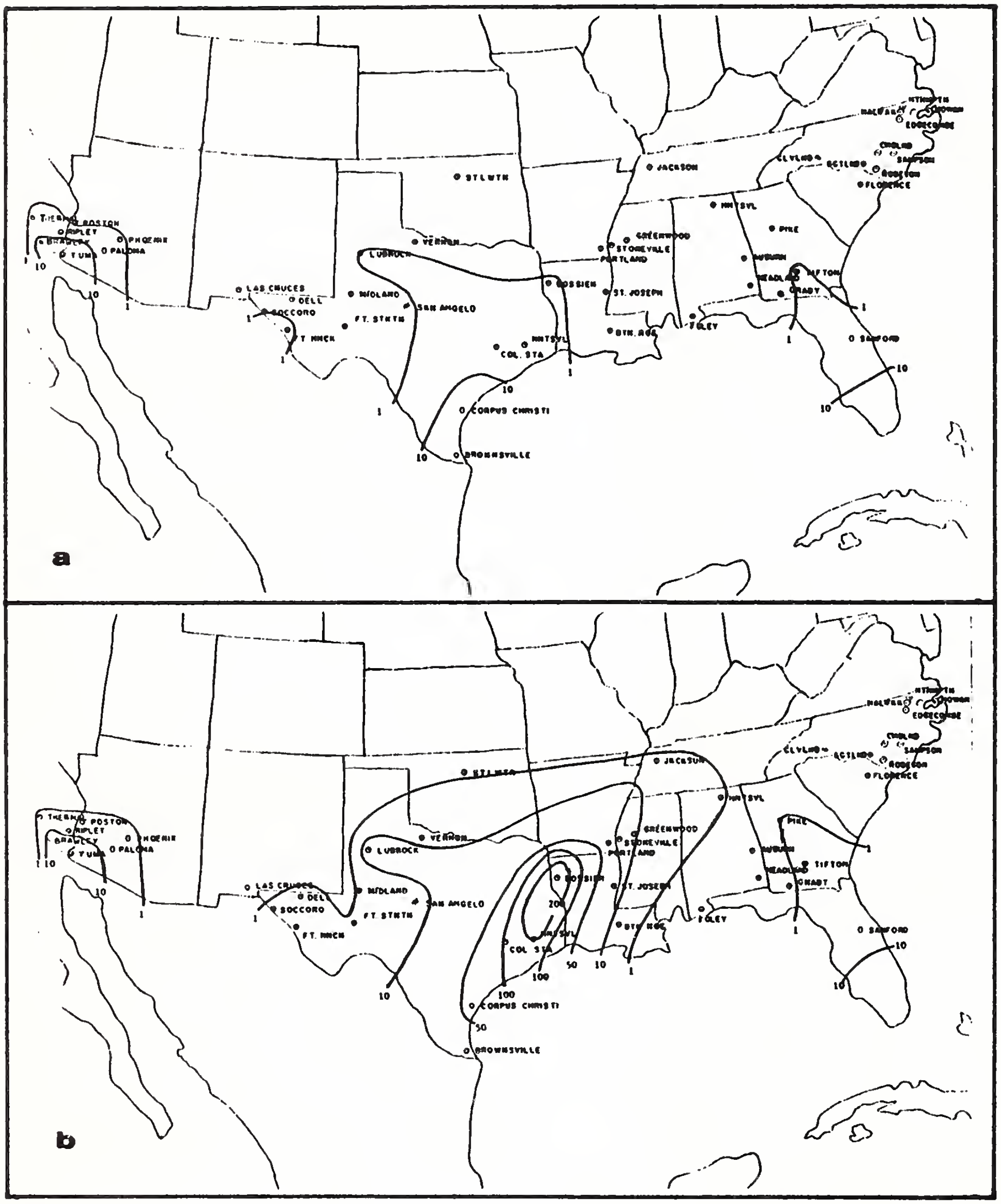

Figure 2
a, Peak number of CEW moths per trap per night caught on or before day 70 (March 11, 1982). b, Peak number of CEW moths per trap per night caught on or before day 80 (March 21, 1982).

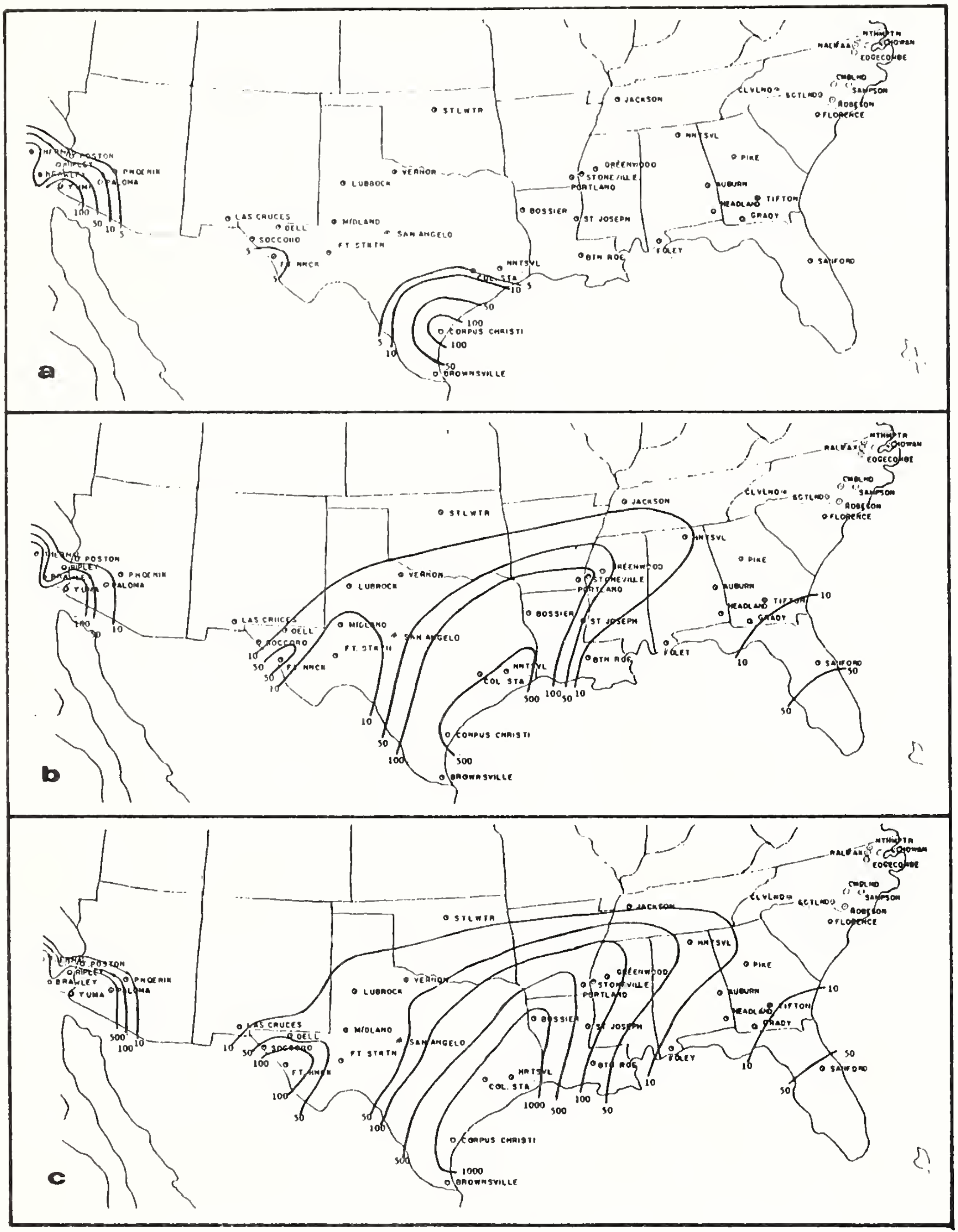

Figure 3
a, Accumulated number of CEW moths per trap caught through day 70 (March 11, 1982).
b, Accumulated number of CEW moths per trap caught through day 80 (March 21, 1982).
c, Accumulated number of CEW moths per trap caught through day 100 (April 10, 1982).

These figures suggest that the Corpus Christi area may be a source of CEW moths or that they are bypassing Brownsville by coming from parts of Mexico that are southwest of Brownsville or from the Yucatan Peninsula. During this 10-day period, surface winds were directly from the Gulf of Mexico at Corpus Christi, blowing from the general direction of Yucatan. However, at this time, possible local emergence may also have been occurring around Corpus Christi. On March 22, a cool front passing through the Corpus Christi-Brownsville area caused the surface winds to shift to the north. Trap catches at Brownsville increased from 9 to 63 moths/trap/night in 2 nights, indicating that moths may have moved from north to south with the cool front.

Also, catches began to increase in West Texas east of El Paso. Accumulated catches were also increasing in California and Arizona and in Florida and Georgia; however, the numerical increases in the more northern traps were very small compared with the increases in Texas, Louisiana, and Arkansas. The accumulated catches by April 10 (fig. 3c) showed trends very like those of March 21.

By April 10, local emergence was probably occurring in southeast Texas and Louisiana, which contributed to moth populations in Arkansas, Mississippi, Tennessee, and Alabama. Little change had occurred, however, in the Southeast United States or in California and Arizona.

A very different pattern of captures was observed in the accumulated catches of the TBW moths per trap (fig. 4). Very few moths had been captured by March 11 except in California and Arizona. By March 31 (fig. 4a), catches of TBW were occurring in the West, south Texas, Florida, and south Georgia. As time passed (fig. 4b, April 10, and fig. 4c, April 30), the TBW catches occurred farther north as would be expected because of normal advancement of warmer weather in the spring. Catches were much higher at Tifton, GA, than at any of the surrounding locations. We don't know why. Also, catches of TBW were very high in California and Arizona. The winds we believe were carrying CEW moths northward could also transport TBW; it is worth noting, then, that during this time, numbers of TBW were very low in South Texas (fig. 4) and Mexico.

The pattern of male TBW emergence from overwintering and capture in pheromone-baited traps at College Station, TX, is shown in figure 5. The first TBW male emerged on April 1, 1982, and captures in the pheromone-baited traps followed the pattern of emergence from overwintering. Only two male CEW's emerged from the study plot on April 17 and 19. This is very little evidence to go by for CEW but it does show that TBW males emerged before CEW males. It has also been reported by others (Fife and Graham 1966, Neunzig 1969, and Gross et al. 1975) that TBW moths normally emerge from diapause before CEW. Hartstack et al. (1982) also found that TBW emerged before CEW at College Station in 1981.

Atmospheric Transport Opportunities

For the South in general, temperatures during March 1982 averaged 1° to 3°C above long-term averages, but the first 10 days during April were well below average. These temperature patterns suggest more frequent low-level winds from the south during March than normal and much more frequent winds from the north during the first 10 days of April.

Figure 6 shows the frequency of days low-level winds were from a southerly direction from March 1 through April 20, 1982, and is a simple index of regional transport opportunities from south to north. The map shows that the frequency of days with airflow from the south ranged from a high of 58 percent in south Texas

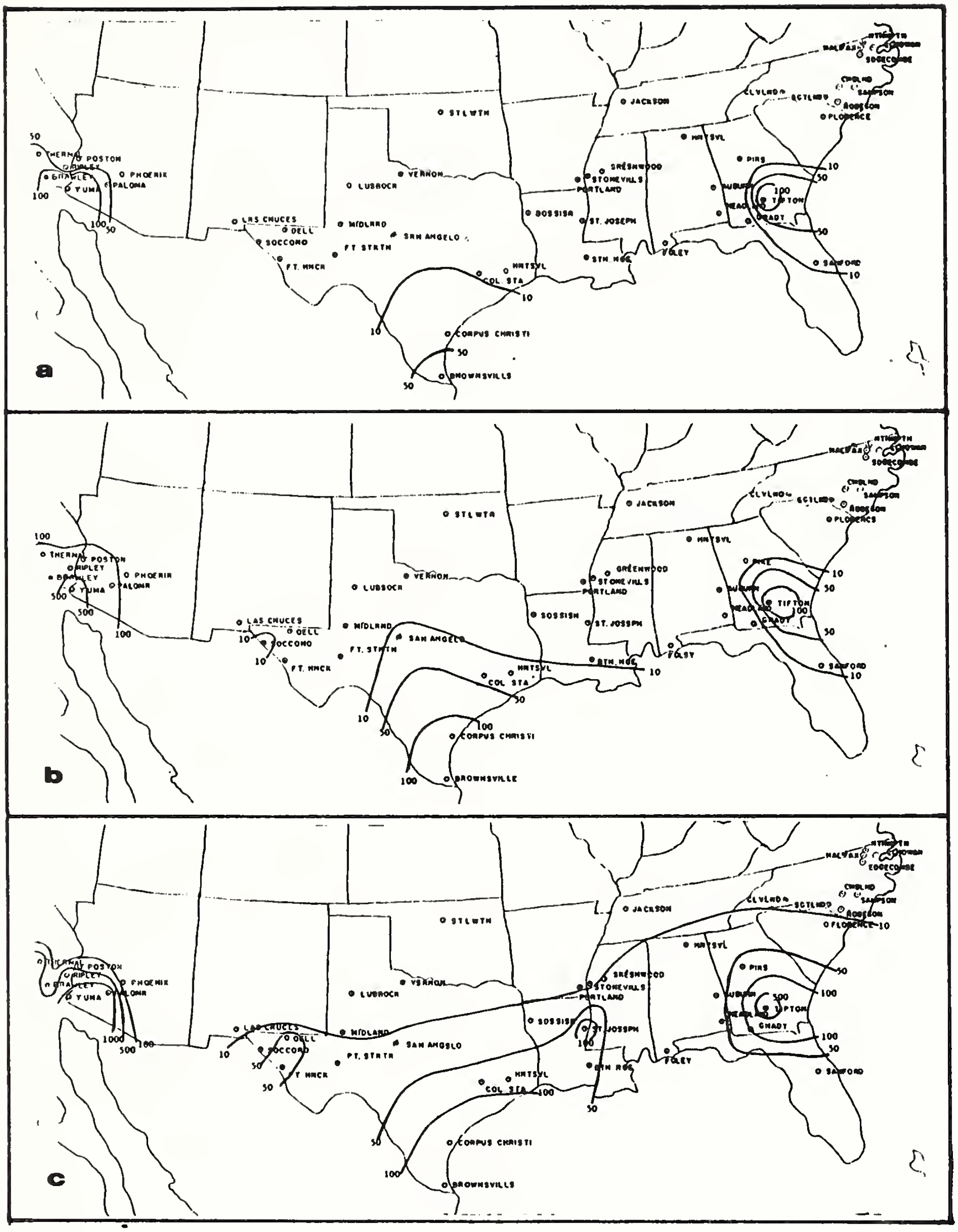

Figure 4
a, Accumulated number of TBW moths per trap caught through day 90 (March 31, 1982).
b, Accumulated number of TBW moths per trap caught through day 100 (April 10, 1982).
c, Accumulated number of TBW moths per trap caught through day 120 (April 30, 1982).

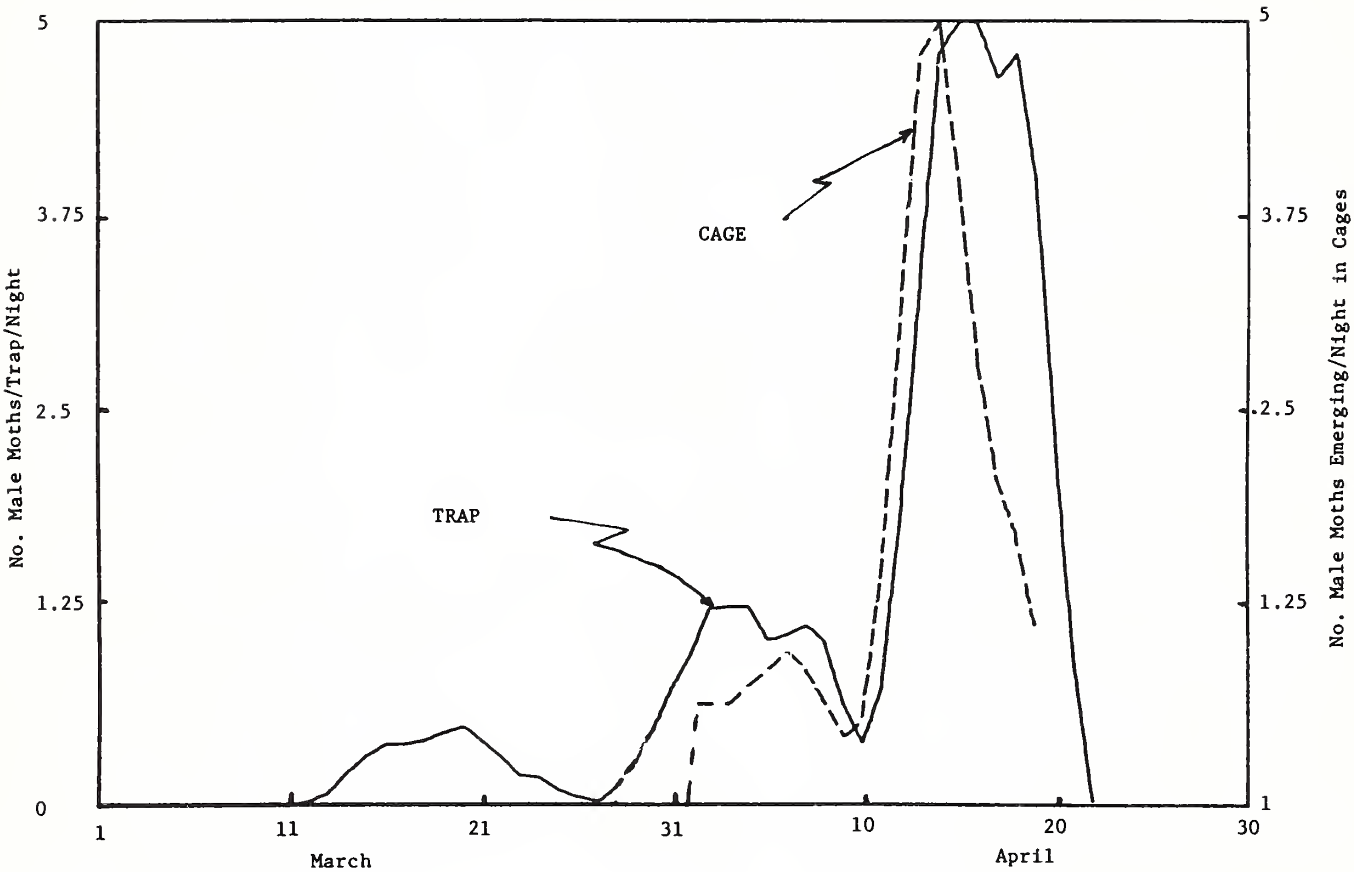

Figure 5
a, Emergence from overwintering and capture in pheromone-baited traps of male TBW's at College Station, TX, in 1982.

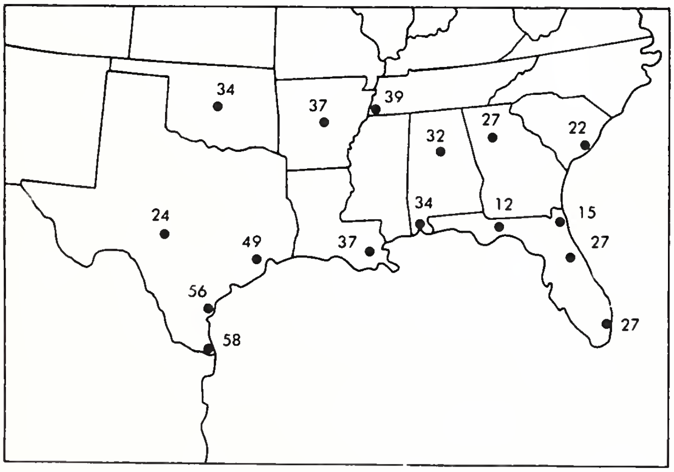

Figure 6
Frequency (percent) of days with surface winds from south to north, March 1-April 10, 1982.

to a minimum of 12 percent over the Florida Panhandle, eastern Alabama, and southern Georgia.

Figure 7 shows the atmospheric transport potential for the same period. The data in the figure are an index of cumulative windspeed when the airflow was southerly. This map emphasizes the considerable opportunities for transport northward from southern Texas over the southern Great Plains and the lower Mississippi River Valley as contrasted with minimal opportunities across northern Florida, eastern Alabama, and southern Georgia.

Comparison of figure 1a, which shows the dates of the first captures of CEW moths, with the pattern of atmospheric transport

potential in figure 7 is striking. The association of the date of first catch and transport opportunities north and northeastward from southern Texas is clear. The maps also suggest a similar association with transport from a source region in southern Florida northward into eastern Georgia and South Carolina, but the transport frequencies and opportunities are much less along the East Coast. Both maps also show an association between reduced transport opportunity and an absence of a source region to the south over the Gulf of Mexico and delayed first-capture dates in northwestern Florida and southern Alabama. Indeed, figure 1a shows that the first capture of CEW moths was about a month later at Auburn, AL, than the first capture of CEW moths to the east at Tifton, GA, or to the west at St. Joseph, LA. There are no obvious thermal or phenological explanations for this lag in southern Alabama and northwest Florida.

The variability of the atmospheric circulation tends to produce runs of days with transport potential towards either the north or the south. Sometimes, however, there are progressions of days with transport potential first to the north,

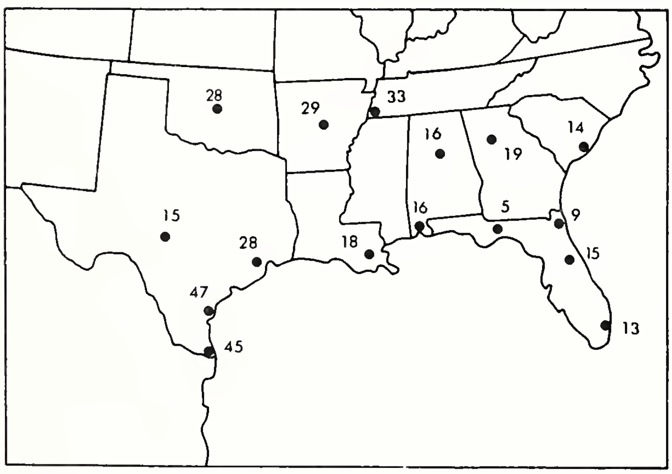

Figure 7
Index of atmospheric transport potential from south to north, March 1-April 10, 1982.

then to the south, and then back again to the north. These periods may be as short as 2 days with the length of the cycle dependent on the speed of the progression of midlatitude cyclones and associated fronts eastward across the United States.

In 1982, for example, there was a sequence of 8 days from March 13 through March 20 when transport potential over southern and central Texas (College Station) was nearly continuous from south to north (fig. 8). In contrast, figure 9 shows a similar run of 8 days from March 22 through March 29 when the transport potential was mostly from north to south. During this period, however, air temperatures at the surface and aloft were probably cold enough to inhibit or reduce CEW activity. The 8-day run of airflow from the north was interrupted only on March 25, when frontal movements allowed for a brief regional flow of air from the south.

Conclusions

Hartstack et al. (1982) concluded that the CEW moths trapped before early April in 1981 had to come from sources south of College Station, TX. The 1982 study reported here adds more evidence that long-range movement of CEW moths is occurring during early spring. Not only did CEW moths again appear before TBW moths, but they were caught 2 weeks earlier than in 1981 and in larger numbers. The large catches were during a continuous 10-day run of southerly winds between March 10 and 20, 1982. Long-range movement of CEW moths into the Southeastern United States was evidently negligible during 1982. No evidence of significant movement of TBW moths into Texas and the lower Mississippi Valley was found.

The run of days with transport potential from south to north shown in figure 8 is typical of spring in southern and eastern Texas. This circulation pattern is associated with midlatitude cyclones to

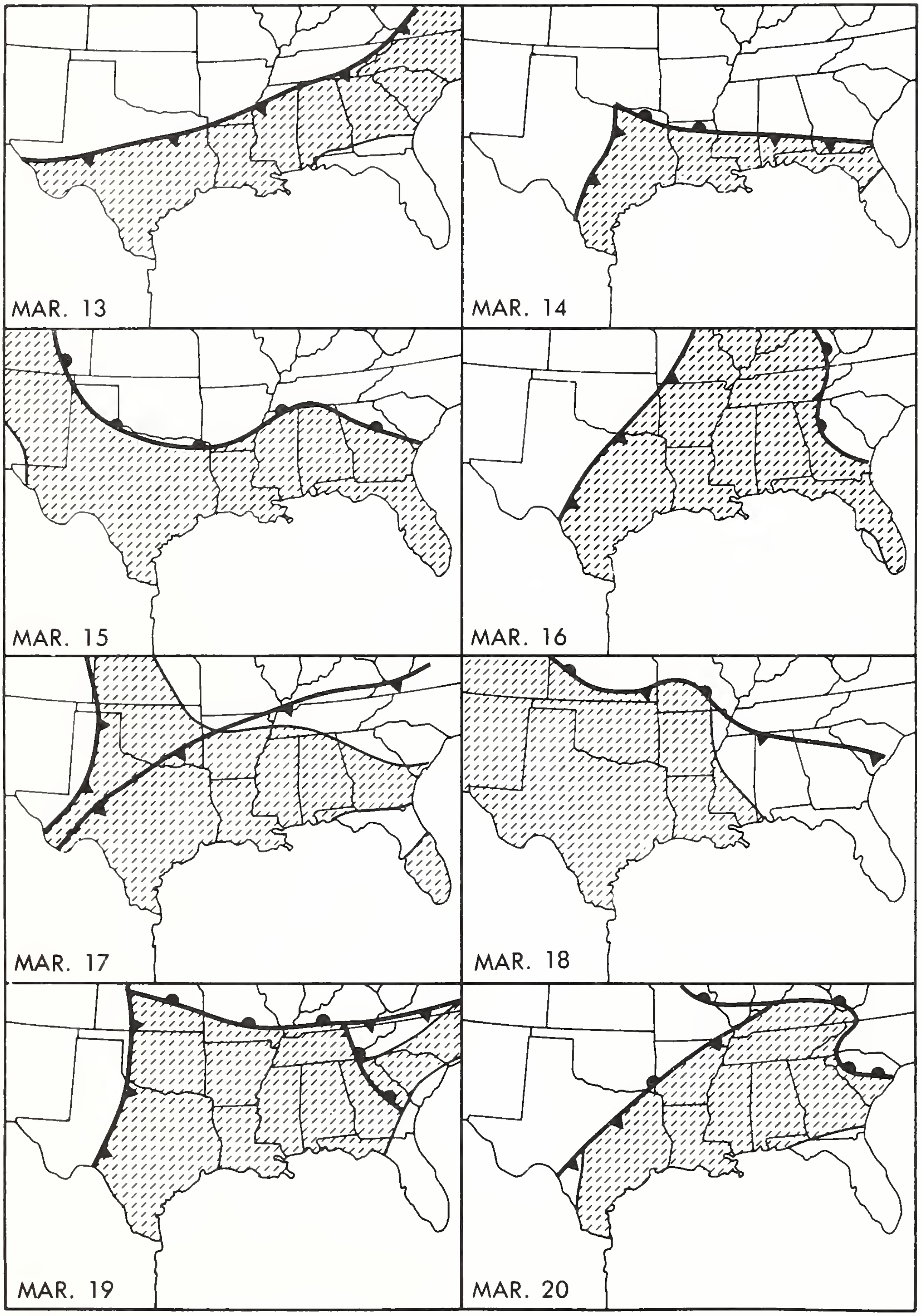

Figure 8
Areas of south-to-north transport potential (shaded), March 13-20, 1982.

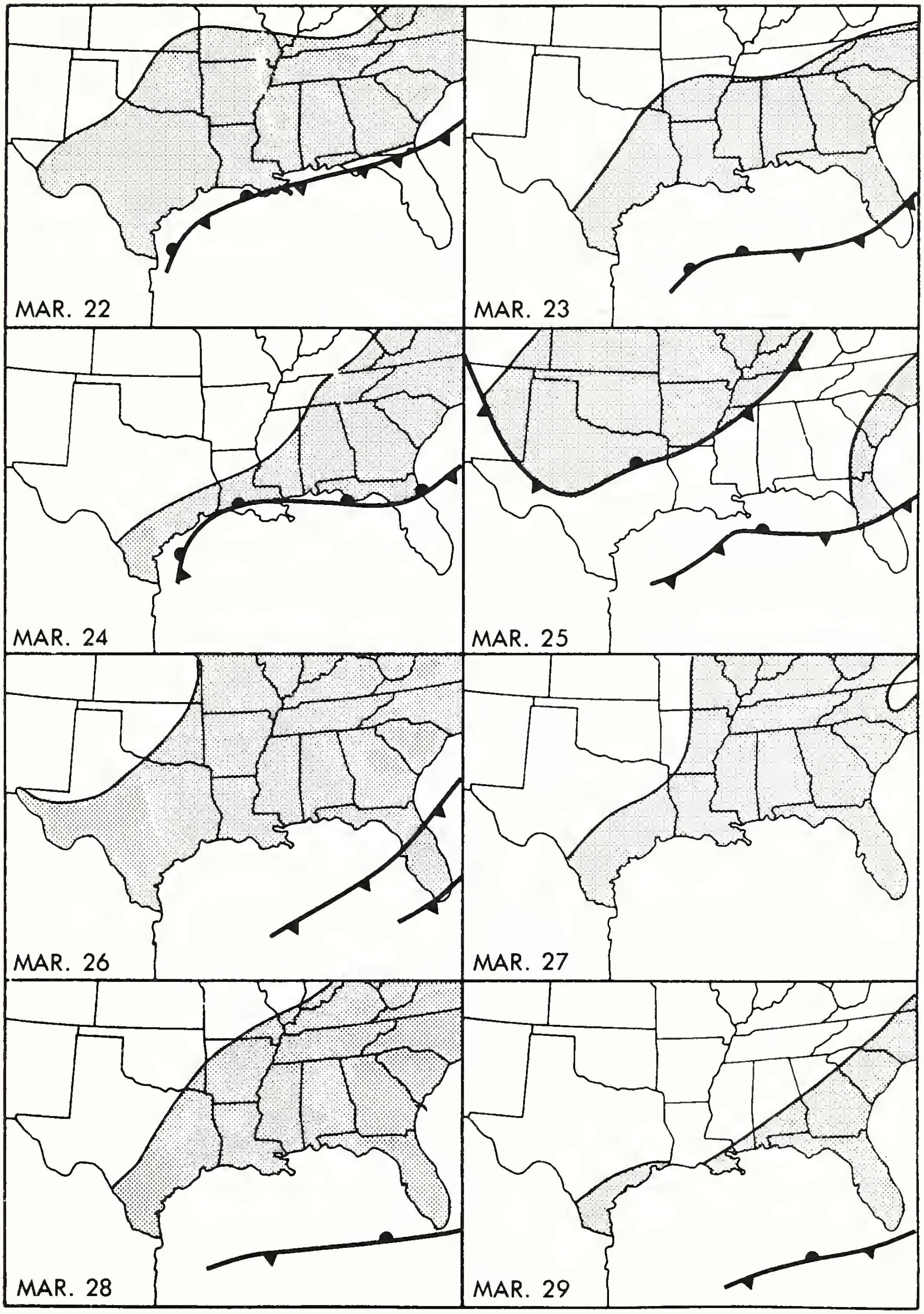

Figure 9
Areas of north-to-south surface airflow (no transport potential towards the north, shaded), March 22-29, 1982.

the north and a low-level jet from southwest to northeast ahead of the trailing surface cold front. This weather pattern provides transport opportunities for airborne organisms and other aerosols to be moved rapidly from northeast Mexico and southern Texas northward across the Great Plains and northeastward up the Mississippi River Valley. Recognition of these transport opportunities is valuable for studying a wide range of pest problems.

Acknowledgments

The research reported in this paper was done in cooperation with the Texas Agricultural Experiment Station, Texas A&M University, College Station. This research was supported in part by a grant from Cotton Incorporated, Raleigh, NC, Project No. 82-535. We thank the many cooperators who contributed to this project by operating traps, collecting data, and sharing it with us.

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JHS

CLIMATIC OPPORTUNITIES FOR THE LONG-RANGE MIGRATION OF MOTHS

Robert A. Muller and Nancy L. Tucker[1]

Abstract

This paper discusses the climatic opportunities for atmospheric transport of insect populations. It demonstrates that climatic conditions during late winter and early spring each year favor transport of insects northward across the Southern United States. Normal climatic patterns allow for long-range migration of moths northward in late winter and spring from Mexico to the southern Great Plains and the lower Mississippi River Valley. Climate for these atmospheric conditions is described in terms of synoptic weather types. The paper also demonstrates that the climate would allow migration southward in the fall along the East Coast to Florida and the West Indies and that frequent opportunities exist for transport westward along the northern margins of the trade winds back to Mexico and Central America.

Introduction

Interest in the airborne transport of flying insects developed early in the 20th century (Glick 1939). By the early 1950's much evidence for the long-range transport of locusts across much of Africa and southwestern Asia had been amassed by Rainey (1951), and more recent studies have shown the relationships of transport to atmospheric circulation patterns and the intertropical convergence zone (Rainey 1979). Beginning in the 1940's, related studies were developed in North America, with considerable work focused on the relationships of spruce budworm moths to the regional and local atmospheric circulation patterns, fronts, and sea breezes over Ontario and the Maritime Provinces in Canada (Greenbank et al. 1980). Here we will not inventory or review the international literature on migration of insects, especially moths, except to state that there is impressive empirical evidence for the long-range transport of moths across extensive bodies of water during favorable weather conditions where there are no significant opportunities for emergence or rest stops; a comprehensive summary volume has been published by Rabb and Kennedy (1979).

The latter part of the paper is obviously speculative, and it is intended to encourage scholarly inquiry into the migration question. If migration does indeed occur, pest-control and management programs will have to be reevaluated, with implications for much of the biological and environmental realms, far beyond the limited range of species transport investigated during these studies.

Corn Earworm Moths in Texas and Backtracking of Transport Opportunities

A.W. Hartstack, J.D. Lopez, and J.R. Raulston have intensively studied the early season appearance of corn earworm moths in Texas by means of pheromone traps. The work reported for the 1981 season by Hartstack et al. (1982) is unique in that the studies strongly suggest that corn earworm moths could not have emerged near College Station, TX, by March 30 and that the large number of moths caught in the pheromone traps must have been transported to College Station by favorable surface winds from the south and southwest.

To assess the atmospheric transport potential for that study, we looked first at weather conditions between the surface and the 850-millibar level (on the average about 5,000 feet, or about 1.6 km, above sea level) during the 12 hours of darkness between 6 p.m. and 6 a.m. (1800 CST and 0600 CST) before mornings when the catch of corn earworm moths was high. Surface weather data observed at 31 synoptic stations in Texas are mapped by meteorol-

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ogists at the National Meteorological Center near Washington, DC, for every third hour, and these maps are available on microfilm from the National Climatic Data Center of NOAA (National Oceanic and Atmospheric Administration) in Asheville, NC. Upper-air observations are normally taken only twice each day; they are synchronized on a global basis, and the observations in the central time zone, including all of Texas, are conveniently at 0600 and 1800 hours CST, very close to sunrise and sunset in Texas during the period of interest in late winter and early spring. The density of the upper-air stations is much less than at the surface synoptic stations, and there are only eight upper-air stations in Texas. Fortunately, atmospheric properties aloft do not normally exhibit the sharper discontinuities often observed within the surface air, and it is realistic to interpolate thermal and wind properties aloft between upper-air stations when fronts and disturbed weather are not present. The 850-millibar level is the lowest of the standard charts of North America prepared routinely twice a day at the National Meteorological Center, and these charts are also available on microfilm from the National Climatic Data Center in Asheville.

Figure 1 shows representative examples of backtracking of the airflow and transport opportunities to Raymondville, in southern Texas, during early March 1981, when corn earworm moth activity, as indexed by trap data, was high (Hartstack et al. 1982). Figure 1a is an example of the transport potential during southerly winds (airflow and transport potential from south to north) overnight on March 6 and 7, 1981. The right-hand curve represents the surface airflow within the first 10 meters of the surface; if the moths had been airborne for the full 12 hours from 1800 CST on March 6 to 0600 CST on March 7, they would have had to originate from a point in the Gulf of Mexico, obviously an unrealistic source.

At the 850-millibar (1.6-km) level, the airflow is from the southwest, rather than from the southeast as the surface, and the speed at the 850-millibar level is much higher than that of the surface air. This trajectory indicates that moths airborne for the full 12 hours at the 850-millibar level and flying with the wind would have originated from a point about 200 km southwest of Raymondville in northeastern Mexico. The middle curve is an average of the vector analyses of the surface and 850-millibar levels, and it is assumed to represent a trajectory at intermediate levels about 0.8 km (2,500 ft) above the surface. Assuming that the moths always fly with the wind during migration, they would have had to originate somewhere within the crosshatched area, with the precise origin depending on the number of hours and altitudes of flight. It will be shown later that figure 1a is representa-

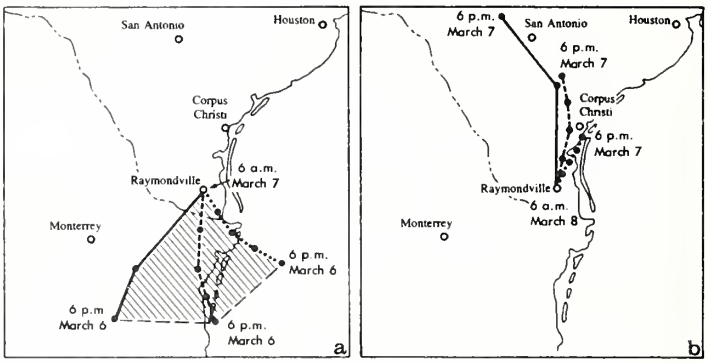

Figure 1
Representative examples of backtracking of airflow and transport opportunities to Raymondville, in southern Texas, during early March, 1981. The dotted curve represents surface air, the continuous curve flow at the 850-millibar (about 1.6-km) level, and the dashed curve flow at approximately the 0.8 km level. A, airflow and transport potential from south to north. B, airflow and transport potential from north to south.

Source: Hartstack et al. (1982); reprinted by permission of Southwestern Entomologist.

tive of typical weather situations for transport potential from south to north.

Figure 1b, in contrast, is an example of transport potential during northerly airflow, one night later on March 7-8 after passage of a cold front. The symbols for the trajectories of the surface and 1.6- and 0.8-km airflows are the same as in figure 1a. Figure 1b shows the narrow arclike band corn earworm moths would have originated from had there been a significant catch of moths on the morning of March 8, 1981, but much lower air temperatures in the polar air following the cold front inhibited moth flights. In summary, the trajectory analysis delimits the possible areas of origin, assuming that the moths fly with the wind at levels up to about 1.6 km sometime overnight.

Figure 2 is a second illustration of backtracking weather very favorable for moth transport when numerous moths were caught in the traps (Hartstack et al. 1982). Figure 2a shows the atmospheric potential for transport in terms of trajectories to College Station, TX, associated with the large catch of corn earworm moths in pheromone traps on March 31, 1981. Figure 2b is a similar trajectory analysis to Portland, AR, where corn earworm moths were also trapped, for the same date as for College Station.

Assuming the moths are inactive during daylight hours, the trajectories in figure 2 are for two consecutive 12-hour overnight flights, with 12 hours of rest time during daylight. Both maps show shorter trajectories of the surface air from the southeast and south and the much longer trajectories of the air at 1.6 km from the south to the west-southwest. Comparison of the trajectories to College Station and to Portland show that they are quite similar. These trajectories, the surface air moving at slow-to-moderate speeds from the south or southeast and the air at 1.6 km moving at much greater speeds from the southwest, are generally

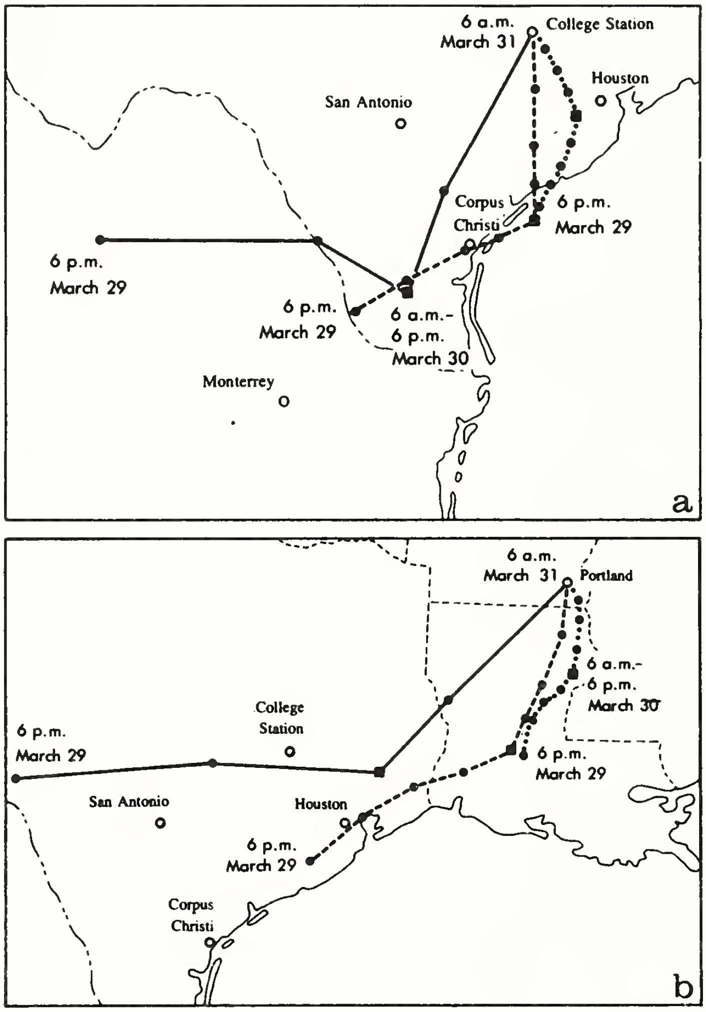

Figure 2
Representative examples of backtracking of airflow and transport opportunities, from south to north, in southern Texas and across the lower Mississippi Valley, during late March 1981. The dotted curve represents surface air, the continuous curve flow at the 850-millibar (about 1.6-km) level, and the dashed curve flow at approximately the 0.8 km level. A, airflow and transport opportunities to College Station, TX. B, airflow and transport opportunities to Portland, AR.

Source: Hartstack et al. (1982); reprinted by permission of Southwestern Entomologist.

characteristic of the Gulf Return (GR) weather type, which will be described briefly in a next section. We believe that the GR weather type is the primary mechanism that transports corn earworm moths northward and northeastward from Mexico and southern Texas over the southern Great Plains and the Mississippi River Valley in late winter and early spring. Note, for example, the great potential for long-distance transport in figure 2 if the moths attain altitudes of close to 1.6 km and remain airborne for most of the night. As an extreme example, assume that the moths remained airborne for 12 hours both nights at altitudes of near 1.6 km. The trajectories in figure 2 suggest that the moths arriving at College Station and Portland could have originated 36 hours earlier more than 400 km southwest of College Station in northern Mexico and more than 500 km west-southwest of Portland near Del Rio, TX.

The geographical extent of this transport potential is illustrated in figure 3, which is a reproduction of a standard surface weather map of the United States for April 3, 1981, published in the weekly series by NOAA. This map shows the GR

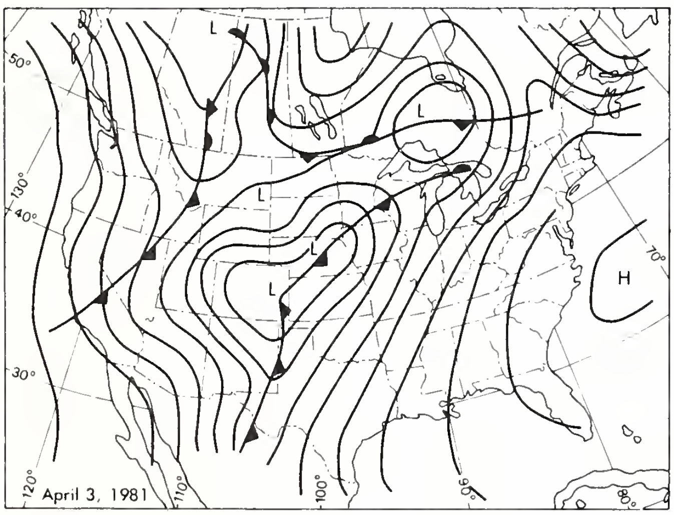

Figure 3
Surface weather map of the United States showing extent of warm, moist southerly flow into the United States, April 3, 1981.

weather, a warm, moist flow of air from the south, extending from the Gulf of Mexico and southern Texas to the Great Lakes and from the Appalachians westward to the Great Plains. Throughout this vast region, the southerly flow of warm, moist air from the south provided excellent opportunities for moth transport during the night.

Expectable Patterns of Atmospheric Pressure, Winds, and Regional Climates

The seasonal regimes of incoming solar radiation are well enough understood that quite precise predictions of daily or hourly values of incoming solar radiation at the top of the atmosphere for any place on Earth can be generated by computer programs. When the seasonal patterns of solar radiation absorption at the surface and in the atmosphere are analyzed, it becomes obvious that there is a net gain of solar radiation at the surface and in the atmosphere during the summer season all the way from the equator to the pole on the average. During the winter, on the other hand, there is still a net gain of radiant energy in tropical regions, but there is a large net loss of radiant energy, solar minus the long-wave terrestrial or thermal radiation to space, in the middle and higher latitudes. It is this radiant energy gain in tropical regions and radiant energy loss in the middle and higher latitudes that produces the dynamic circulations of the atmosphere and the oceans. The atmospheric circulations are driven by this latitudinal gradient of energy gains and losses; and on a global basis, the circulation patterns are approximately reproduced on an annual cycle.

This generalized global circulation of the atmosphere, modified by the effects of the distribution of continents and ocean basins, as well as the major mountain systems, produces the regional patterns of climate over the Earth. Figure 4 illustrates regional climates of North

America, as classified by the Köppen-Geiger system, the best known for identification of generalized climatic regions on a global basis.

Figure 4 shows that most of the Southern United States is included within the humid subtropical climatic region (Cfa); to the west are the dry climates (BS and BW) of Texas and the Great Plains; to the north are the humid continental climates (Dfa and Dfb); and southern Florida includes a small area of the tropical savanna (Aw) climate. The humid subtropical climate is characterized by mild wet winters and hot humid summers. At this level of generalization, the fall and winter seasons tend to be dominated by a net flow of air away from the continent from north to south, and spring and summer seasons by an onshore flow of air from south to north.

This seasonal reversal of airflow is the basis for the climatic potential for a "closed" seasonal cycle of moth migration. The climatic circulation provides the opportunity for moths to move northward in the early spring from subtropical overwintering sites and then to return to subtropical latitudes during the fall.

Synoptic Weather Types

The average climate is not a realistic measure of climatic opportunities for the migration of moths, however. Instead, it is necessary to evaluate the night-to-night circulation atmospheric patterns, with the working assumption that the moths fly with the wind. Muller (1977) and Muller and Willis (1983) have organized all weather in southern Louisiana into eight synoptic weather types, and these types are useful for an investigation of the climatic opportunities for migration. In their system, the dynamic atmospheric circulation features affecting the local weather are identified from surface weather maps of the United States for 0600 hours CST (near sunrise) and for 1500 hours CST (close to the warmest time of the day on the average), and monthly estimates of weather-type frequencies and average properties for 0600 and 1500 hours CST have been worked out for New Orleans.

The simplified surface weather maps in figure 5 illustrate the eight synoptic weather types in terms of the weather at New Orleans. The nomenclature is for the central Gulf Coast, but the synoptic types with various descriptive names can be adapted anywhere in the United States east of the Rockies. Each of the types along with a brief description is listed below (Muller and Willis 1983).

Pacific High (PH)

The circulation around a deep surface low to the north brings mild and relatively dry air across southern Louisiana after a "Pacific" cold front. PH weather is normally fair and mild with west to northwest winds.

Continental High (CH)

The surface air normally flows southward east of the Rocky Mountains and over the Great Plains and Mississippi River Valley to Louisiana. The source regions for this cold, dry air in winters are in Canada and Alaska, and this weather type is mainly associated with polar or Arctic outbreaks and northerly or northeasterly winds. This weather type is restricted to the fair weather associated with the core of the high-pressure systems.

Frontal Overrunning (FOR)

This cloudy and rainy type occurs often when cold fronts become more or less stationary along the Gulf Coast or over the northern or central Gulf of Mexico. Often "waves" develop along the front over

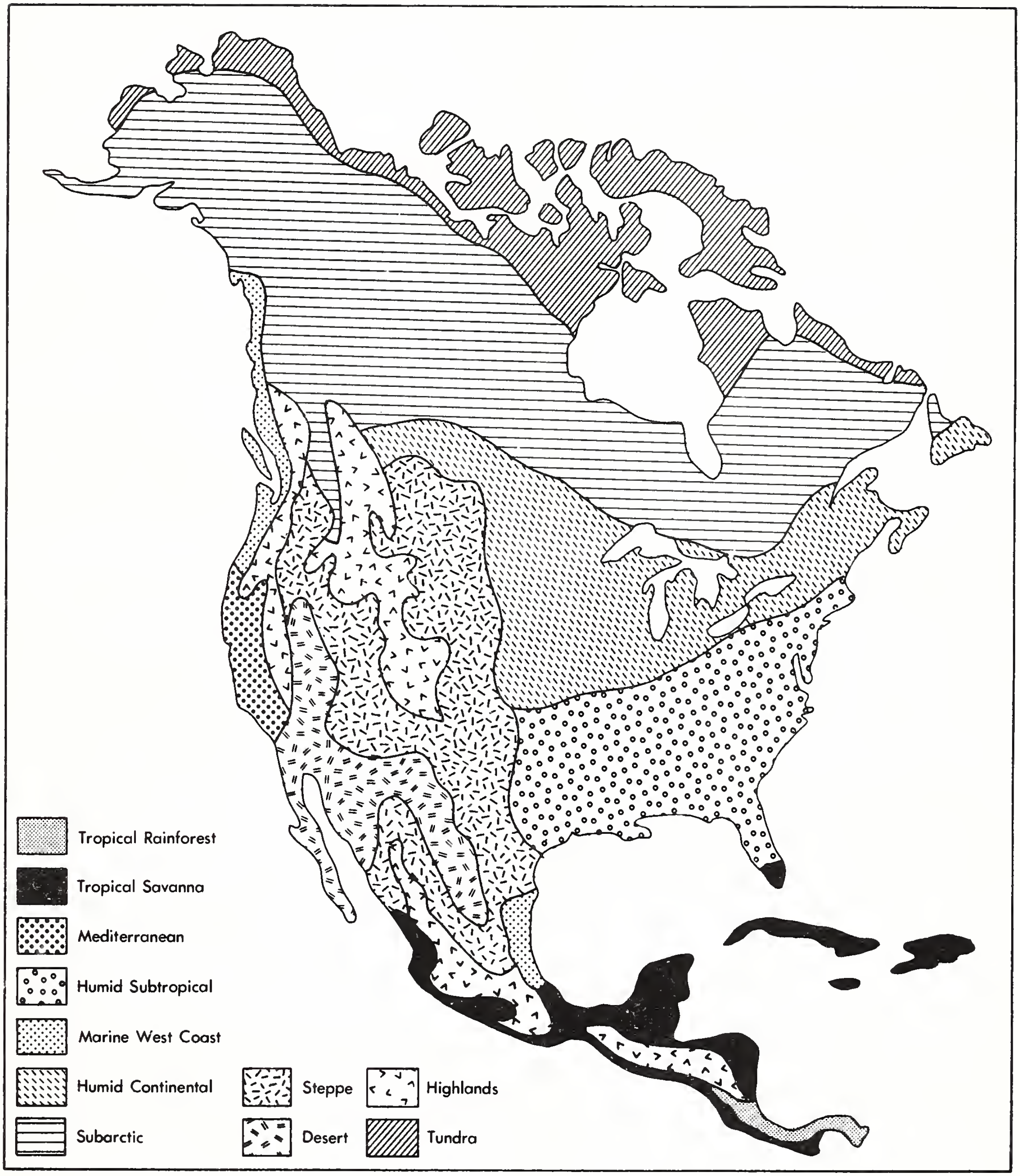

Figure 4
Regional climates of North America, as classified by the Köppen-Geiger system.

Source: The Odyssey World Atlas, 1966.

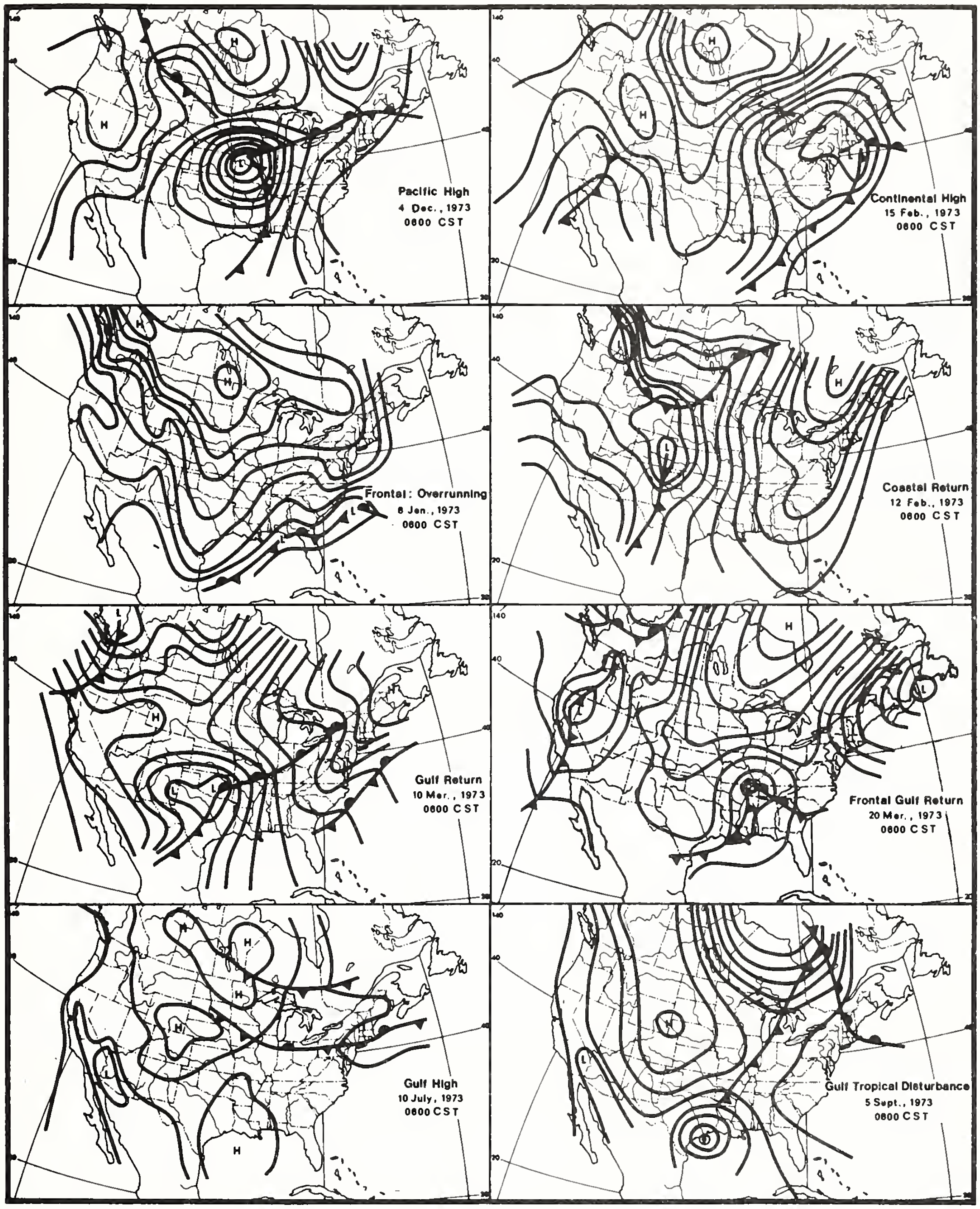

Figure 5
Representative examples of the eight synoptic weather types affecting weather at New Orleans, LA.

Source: Muller and Willis (1983).

the western Gulf and then sweep northeastward bringing heavy clouds, northeasterly winds, and precipitation to southern Louisiana.

Coastal Return (CR)

When the crest of a high-pressure ridge drifts to the east of Louisiana, surface winds over New Orleans veer from the northeast to the east and southeast. During winter and spring, the fair and mild weather is associated with continental polar air modified by short passages over the Atlantic and Gulf. During late summer and early autumn, this type includes the Bermuda High when hot and humid air flows primarily from the east over New Orleans.

Gulf Return (GR)

When the high-pressure ridge drifts even farther eastward, the surface pressure pattern on the back side of the high usually results in a strong return flow of warm and moist maritime tropical air from the Caribbean Sea and the Gulf of Mexico. In this situation, the pressure gradient is often strengthened by developing low pressure over the Texas Panhandle, which then begins to sweep northeastward. In both of these situations, the flow of modified continental polar air is gradually replaced by moist tropical air as surface winds continue to veer from east to southeast to south.

Frontal Gulf Return (FGR)

When the return flow is affected by lifting and convergence along an approaching cold front from the northwest, the resultant weather becomes increasingly turbulent and stormy. Surface winds are typically from the southwest. FGR weather, therefore, is restricted to warm-sector periods when fronts are close enough to dominate the weather in the New Orleans area, and GR weather includes the periods with the same air but with distant fronts far to the north or west.

Gulf High (GH)

During summer, especially, there are periods when the western extension of the Bermuda High is displaced southward towards or over the Gulf of Mexico and the local circulation is from the southwest.

Gulf Tropical Disturbances (GTD)

During summer and fall, and even occasionally during the late spring, southern Louisiana is sometimes affected by tropical systems that normally drift from east to west across the northern Gulf. These periods of disturbed tropical weather range from relatively weak easterly waves to rare but severe hurricanes, such as Camille in 1969. Wind directions depend on the location and movement of the tropical systems.

The GR and FGR synoptic weather types provide the opportunities for transport of moths generally from south to north. The air-trajectory analyses in figure 2, showing the regions from which corn earworm moths could have originated overnight to arrive at College Station, TX, and Portland, AR, respectively, are also examples of GR weather situations. Trajectories for CH and FOR weather are illustrated in figure 1b, which shows airflow to Raymondville, TX, behind a cold front that crossed southern Texas the day before. When temperatures are warm enough, in the late summer and fall, the CH and FOR weather provide opportunities for the transport of moths generally from north to south.

Long-range transport opportunities during GR and FGR weather are illustrated in figure 6. This figure shows four daily surface weather maps of the United States for April 3-6, 1981. The map for April 3 is the same as in figure 3. The 4-day

sequence of maps shows how the opportunity for transport during the GR and FGR weather is displaced towards the east ahead of the cold front advancing eastward. The maps are for 0600 CST hours, but the isobar pattern in the GR and FGR weather sector assures a meteorologist that the surface airflow each night was mainly from a southerly or southwesterly direction.

Figure 7 shows the 4 following days, April 7-10, 1981. During these 4 days, the GR weather and the transport potential from south to north were set up again with opportunities for moth migration from northern Mexico and southern Texas to the Great Plains and the Mississippi River Valley. In a later section, we will show that this transport potential from south

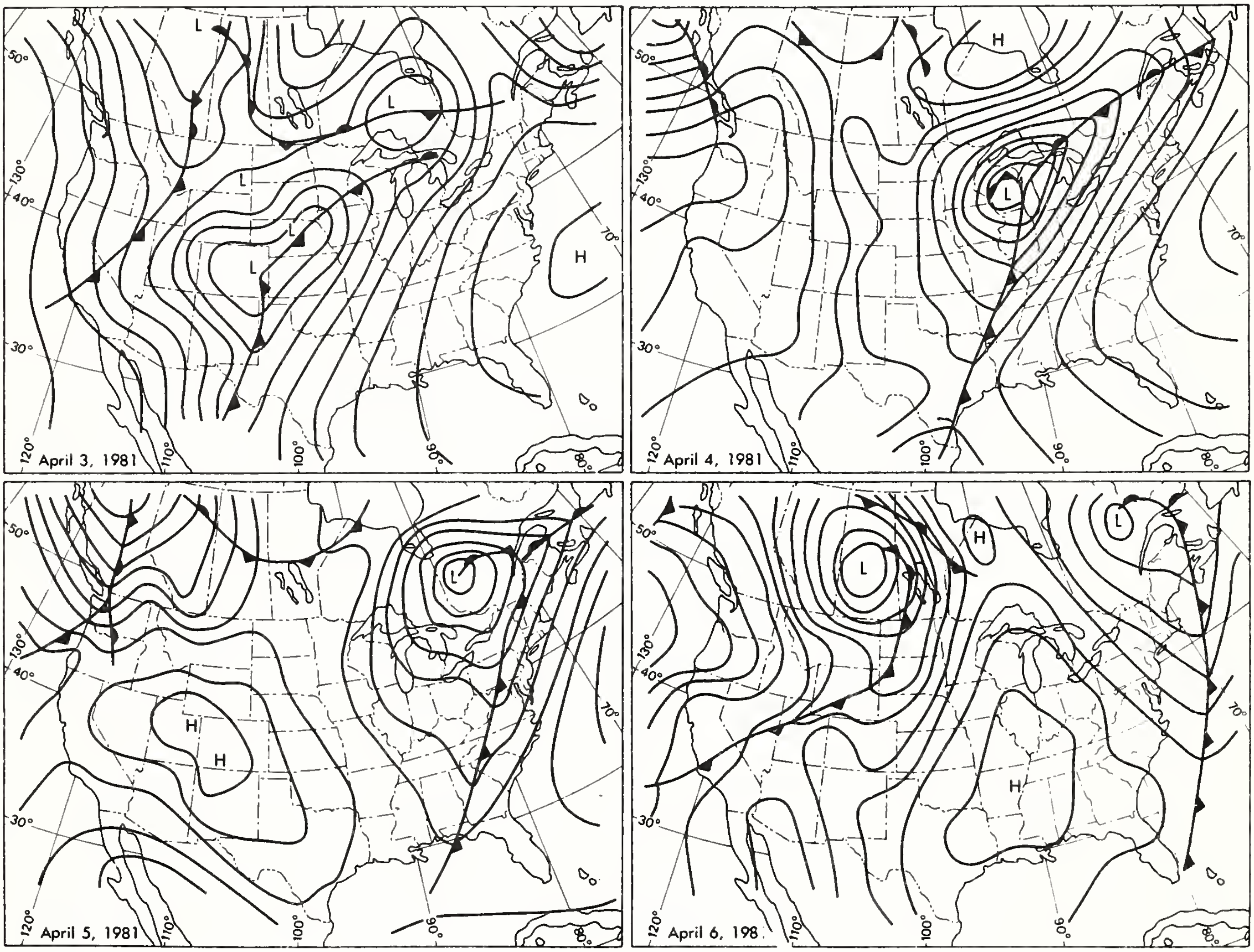

Figure 6
Sequence of four daily surface weather maps of the United States showing displacement of transport opportunity toward the east, ahead of an advancing cold front, during GR and FGR weather, April 3-6, 1981.

to north sets up runs of days each late winter and early spring.

Synoptic Weather-Type Properties in Relation to Transport Potential

Synoptic weather-type properties can be evaluated to determine the atmospheric potential for insect transport. Windspeed and direction and air temperature are the major variables that should be evaluated to determine transport potential. For each place or region, each synoptic weather type has certain wind and temperature ranges associated with it; therefore, it is possible to identify potentially optimum transport nights by synoptic weather type.

Weather types of major interest are GR and FGR, representing airflow from south to north, and CH and FOR, representing

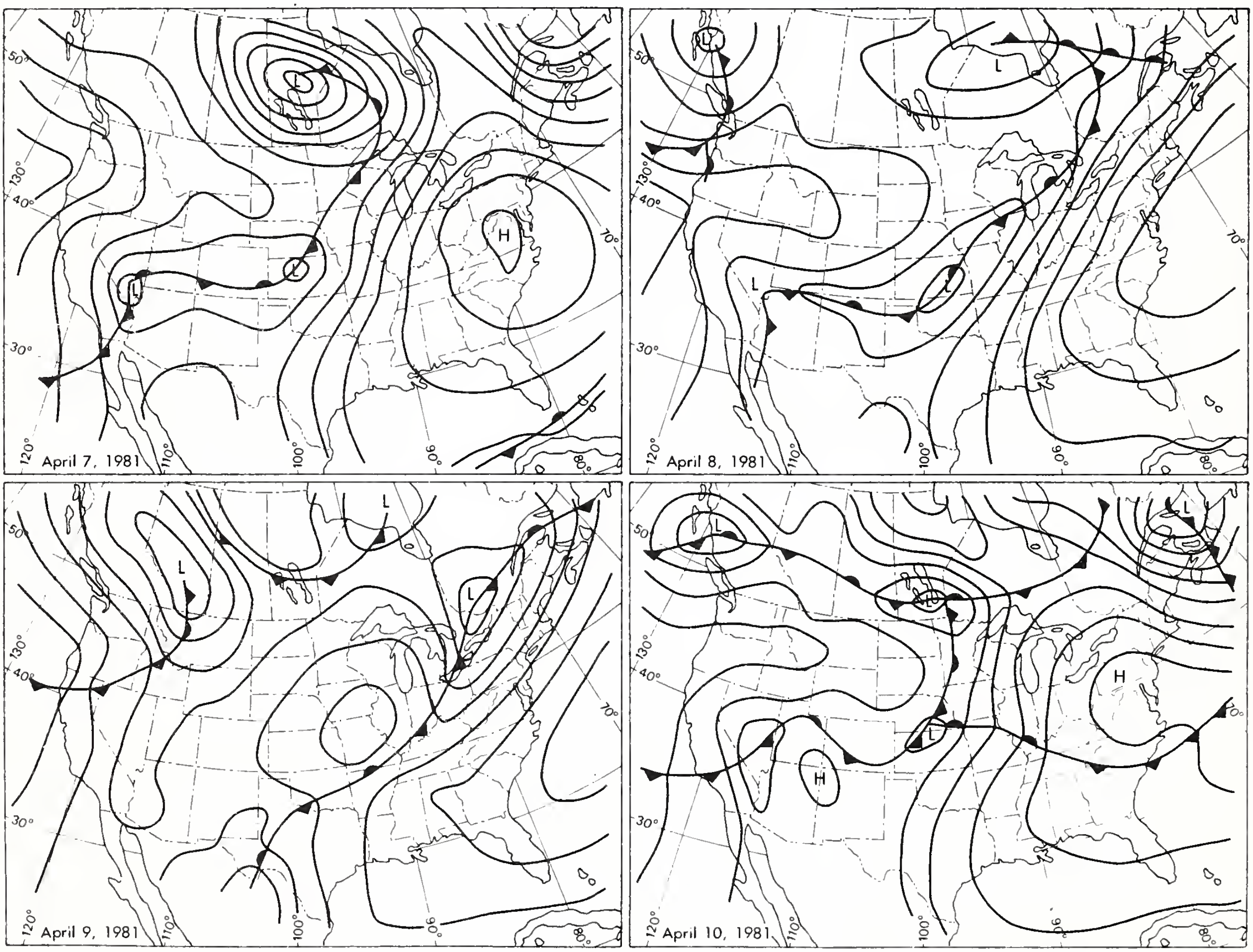

Figure 7
Sequence of four daily surface weather maps of the United States showing transport potential from northern Mexico and southern Texas to the Great Plains and the Mississippi River Valley, April 7-10, 1981.

airflow from north to south. Evidence from prior investigations (Hartstack et al. 1982) suggests that excellent climatic opportunities coincide with major moth migrations during late March and April over Texas. Evidence also suggests that atmospheric opportunities for transport are greatest in spring during GR and FGR weather and that these opportunities recur each year.

Windspeed and direction and air-temperature data were compiled for GR, FGR, CH, and FOR weather types. These data were compiled from weather maps prepared by the National Meteorological Center for 1978-81 and made available on microfilm by the National Climatic Data Center at Asheville, NC. Surface data were compiled from weather maps prepared at 3-hour intervals. The upper-air data at the 850-millibar or 1.6-km level were taken from the constant-pressure charts prepared twice daily from radiosonde data at 0600 and 1800 hours CST. Fortuitously, the radiosonde ascents at 1800 and 0600 hours CST coincide approximately with sunset and sunrise, bracketing the nighttime hours when the moths are likely to be migrating.

Average temperature and wind properties were compiled for two sites with surface and upper-air data printed on the maps. Brownsville, TX, was selected to represent average conditions near where corn earworm moths are likely to fly over into the United States from northeastern Mexico during GR and FGR weather. Shreveport, LA was selected as the second site because atmospheric conditions there should be representative of atmospheric flows entering the lower Mississippi River Valley during GR and FGR weather in late winter and early spring. The same two sites are useful for interpretation of average properties during CH and FOR weather in late summer and early fall when migrating moths may be returning to subtropical latitudes.

Air temperatures at the surface and 850-millibar (1.6-km) levels were plotted on graphs to compare the thermal properties of the GR and FGR weather types with CH and FOR types and especially to ascertain if average thermal properties are warm enough to sustain moth flight. Figure 8 shows individual cases recorded by synoptic weather type for 0600 hours CST at Brownsville in March and at Shreveport in April. Normally, overnight temperatures are coolest at 0600 hours CST, and the clusters of data points in figure 8 provide reasonable measures of the coldest temperatures experienced by moths in flight overnight.

In Figure 8 the graph for March at Brownsville illustrates a marked difference of thermal properties of the two synoptic weather types associated with south-to-north flow when compared with the weather types associated with north-to-south flow. Surface air temperatures during GR and FGR weather range between the mid-50's and mid-70's in °F, and the temperatures aloft at about 1.6-km range mostly between the low 50's and middle 70's; the greatest number of points cluster near the upper margins of the range.

The graph for Shreveport for April, 1 month later and much farther north than Brownsville, shows that thermal properties in the GR and FGR air are also high enough to permit moth flight. Surface temperatures at Shreveport range between the mid-50's to the low 70's, with the range at the 850-millibar level more restricted between the mid-50's and the mid-60's. The flight of most moths is believed to be inhibited at air temperatures lower than the low 50's (A.N. Sparks, personal communication) and the data show that thermal conditions in the GR and FGR weather at the latitude of Brownsville in March, and farther north at Shreveport in April, would rarely restrict moth flight.

On the other hand, figure 8 also shows that the CH and FOR weather, the north-to-south airflow, have much lower temperatures and that the range within the types is greater. Much of the time during CH and FOR weather, at the latitudes of Brownsville in March and Shreveport in April, temperatures at the surface or aloft at 1.6 km or both, are low enough to inhibit moth flight. Later in the spring season, of course, temperatures during these weather types are warm enough not to inhibit north-to-south transport of moths.

Figure 9 summarizes the average thermal properties of the two sets of synoptic weather types at the surface and 850-millibar levels at Brownsville and Shreveport at 1800 hours CST and 0600 hours CST during March and April.

The mean values in figure 9 provide a good measure of the thermal differences between the weather types associated with airflow from northerly or southerly directions and whether moth flight is possible. For example, the average temperatures of GR and FGR weather together at Brownsville at 1800 hours CST in March (about sunset) is in the mid-70's at the surface and about 60°F aloft at 1.6 km. Twelve hours later at 0600 hours CST (near sunrise), the surface air cools to the upper 60's, but the temperature of the air at the 1.6-km level remains about the same, in the lower 60's. Overnight temperatures during March at Brownsville, both at the surface and up to at least the 850-millibar, or 1.6-km, level are warm enough not to inhibit moth flight.

At Shreveport during March, however, the temperatures during the GR and FGR weather are much more marginal to moth flight, and there are times when the air is probably warm enough and other times when it is not. Figure 9 shows that surface

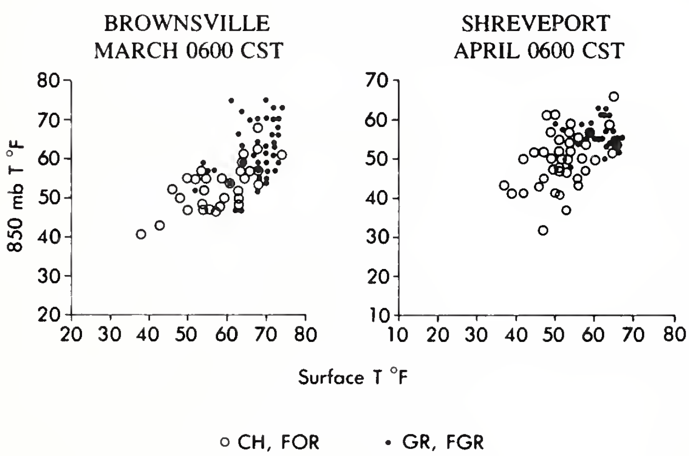

Figure 8
Temperatures at 0600 hours CST at the surface and 850-millibar levels by synoptic weather type at Brownsville in March and at Shreveport in April. Solid dots represent the GR and FGR types (airflow from south to north), and the small circles, the CH and FOR types (airflow from north to south).

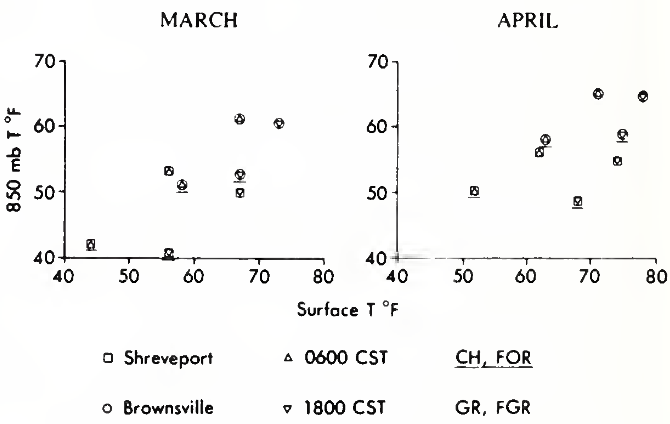

Figure 9
Mean thermal properties by synoptic weather type at the surface and 850-millibar levels at Brownsville and Shreveport at 1800 and 0600 hours CST during March and April. Underscored symbols represent CH and FOR weather, while nonunderscored symbols represent the GR and FGR weather. Brownsville properties are denoted by circles and Shreveport by squares. Small triangles represent 0600 hours CST (near sunrise) when the apex is pointed upward and 1800 hours CST (near sunset) when the apex is pointed downward.

temperatures at 1800 hours CST around Shreveport during these weather situations in March average in the upper 60's, with temperatures at the 1.6-km level about 50°F. By 0600 CST, the surface temperatures fall to the middle 50's, with temperatures aloft slightly warmer than at sunset. The graph for April shows that average temperatures at the surface and aloft are warmer at both cities than for March and that, on the average, temperatures are apparently warm enough to sustain moth flight.

In the spring, the GR and FGR weather types are associated with the horizontal advection of warm maritime tropical air from the Gulf of Mexico into the interior of the United States. Examples of this warm air advection during April 1981 are shown in figures 6 and 7. Thermal properties favorable for moth flight extend from the Gulf Coast up the Mississippi River Valley over the Ohio River Valley and sometimes even to the Great Lakes. During these weather situations, the northern margins of favorable thermal conditions will normally be found near a surface front, with much colder air on the northern side of the front. Figure 9 also shows average thermal properties of the CH and FOR weather to emphasize the differences of average thermal properties among some of the synoptic weather types.

Windspeed is, of course, critical to the atmospheric potential for the transport of moths, and figure 10 is a scatter diagram of windspeeds at the surface and at the 850-millibar, or 1.6-km, level at Brownsville during GR and FGR weather together on the one hand and CH and FOR weather on the other. The plotted data are for 0600 hours CST during March when moth transport towards the north is likely and for 0600 hours CST during October when transport towards the south is a possibility. The wind data are taken from microfilm copies of the synoptic maps prepared by the National Meteorological Center; on the maps, windspeeds are shown by class intervals of 5 knots.

The outstanding feature of figure 10 is the strong windspeeds aloft at the 850-millibar level during GR and FGR weather at Brownsville. During these weather situations, surface winds are normally from the southeast or south, with the airflow at the 850-millibar level normally from the southwest. At 0600 hours during the GR and FGR weather in March, for example, surface winds range normally between 5 and 15 knots, but the flow aloft can range from 10 knots to 50 knots; 30 or more knots are not uncommon! These winds are sometimes referred to as low-level jets and are common to the warm sectors of low-pressure systems ahead of trailing cold fronts. The situation is similar in October, but these weather types do not occur as frequently, and windspeeds are not normally so high.

Figure 10 also shows that winds are not so strong during CH and FOR weather on the

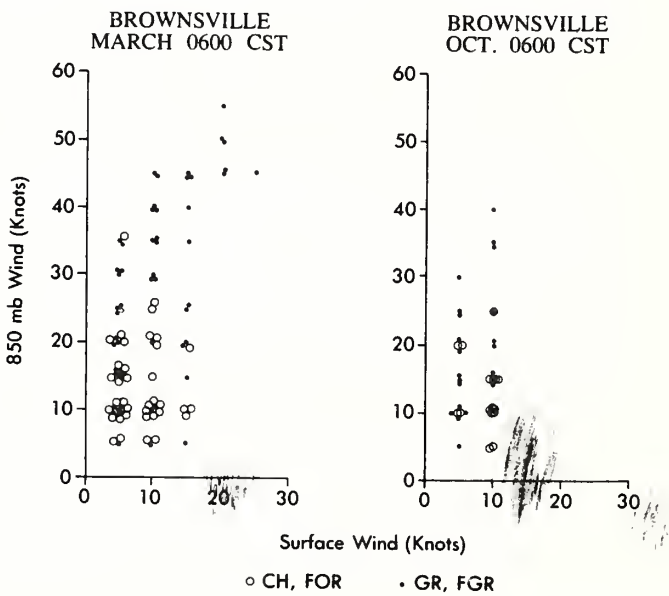

Figure 10
Windspeeds at 0600 hours CST during March and October at the surface and 850-millibar levels at Brownsville by synoptic weather type.

average. This is especially the case at the 850-millibar level, where windspeeds are normally no greater than 20 knots.

Figure 11 is the companion to figure 9; it shows the mean windspeeds at the surface and 850-millibar levels for March and April at 0600 and 1800 hours CST at Brownsville and Shreveport by GR and FGR weather on the one hand and by CH and FOR weather on the other. During GR and FGR weather in March at Brownsville, for example, windspeeds at 1800 hours CST at the surface and 850-millibar levels average about 15 and 19 knots, respectively, and at 0600 hours CST, the corresponding average speeds are 9 and 26 knots. Similarly, at Shreveport the flow aloft averages about 23 knots at 1800 hours CST and much more than 30 knots at 0600 hours CST. During April, the average windspeeds aloft at the 1.6-km level are not quite so dramatic, but at Shreveport they are still greater than 20 knots at both 1800 and 0600 hours CST.

For both months, windspeeds during CH and FOR weather are not so strong, especially

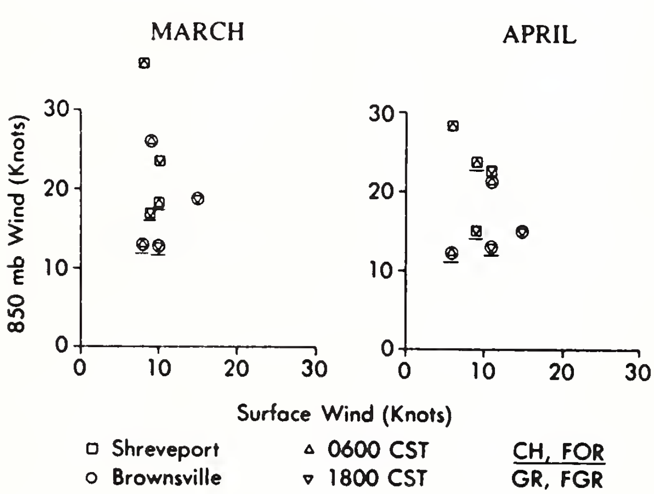

Figure 11
Mean windspeeds at the surface and 850-millibar levels for March and April at 0600 and 1800 hours CST at Brownsville and Shreveport by synoptic weather type.

by contrast at the 850-millibar level, where windspeeds average mostly between 10 and 20 knots.

Study of the weather maps suggests strongly that these average properties of temperature and windspeed and direction are characteristic of GR and FGR weather throughout the warm sectors to the south of the frontal systems of midlatitude storm systems during late winter and spring. Each place has its own average properties, but opportunities for moth transport to the north and northeast normally recur time and time again each late winter and spring. The backtracking examples of transport potential to College Station, TX, and Portland, AR, in figure 2 are representative of these weather and transport situations.

Frequency and Persistence of Northerly and Southerly Flow for Transport in the Southern United States

We have established that atmospheric properties are favorable for the transport of moths from northeastern Mexico northward and northeastward across Texas over the Great Plains and the lower Mississippi River Valley in late March and April during GR and FGR weather and that these weather situations recur from time to time each and every year. Figure 12 shows the days in March when the surface winds were from southerly or northerly components for 5 years between 1971 and 1975 at Miami, FL, and Brownsville.

Miami and Brownsville were selected to represent the eastern and western margins of the transport potential across the southern United States within the humid climatic realm. Winter temperatures at Miami and Brownsville are very mild, and these two areas are also possible sources of overwintering for some moth species. Figure 13, a companion to figure 12, represents similar measures of transport potential farther north at Atlanta, GA, in the east and Shreveport to the west.

Windspeed and wind-direction data were compiled from the surface weather maps prepared at the National Meteorological Center of the National Weather Service for 0700 hours EST and published in the weekly series. Northerly flow (transport towards the south) includes azimuths from 60° to 300°; southerly flow (transport towards the north) includes azimuths from 120° to 240°. Therefore, northerly and southerly flow together include 67 percent of all possible wind directions.

Perusal of figure 12 shows that southerly flow (transport potential to the north) occurred on 60 percent of the March days between 1971 and 1975 at Brownsville. Even at 0600 hours CST, surface winds are generally at speeds of 10 knots or greater; and the flow aloft during GR and FGR weather (almost all of the southerly flow cases are associated with these two weather types) is much stronger than at the surface.

Another outstanding feature of figure 12 is the daily persistence of southerly flow at Brownsville. It is not uncommon for southern Texas to experience a run of 3 or 4 days with southerly flow; note especially the 12 consecutive days of southerly flow at the beginning of March 1974. The

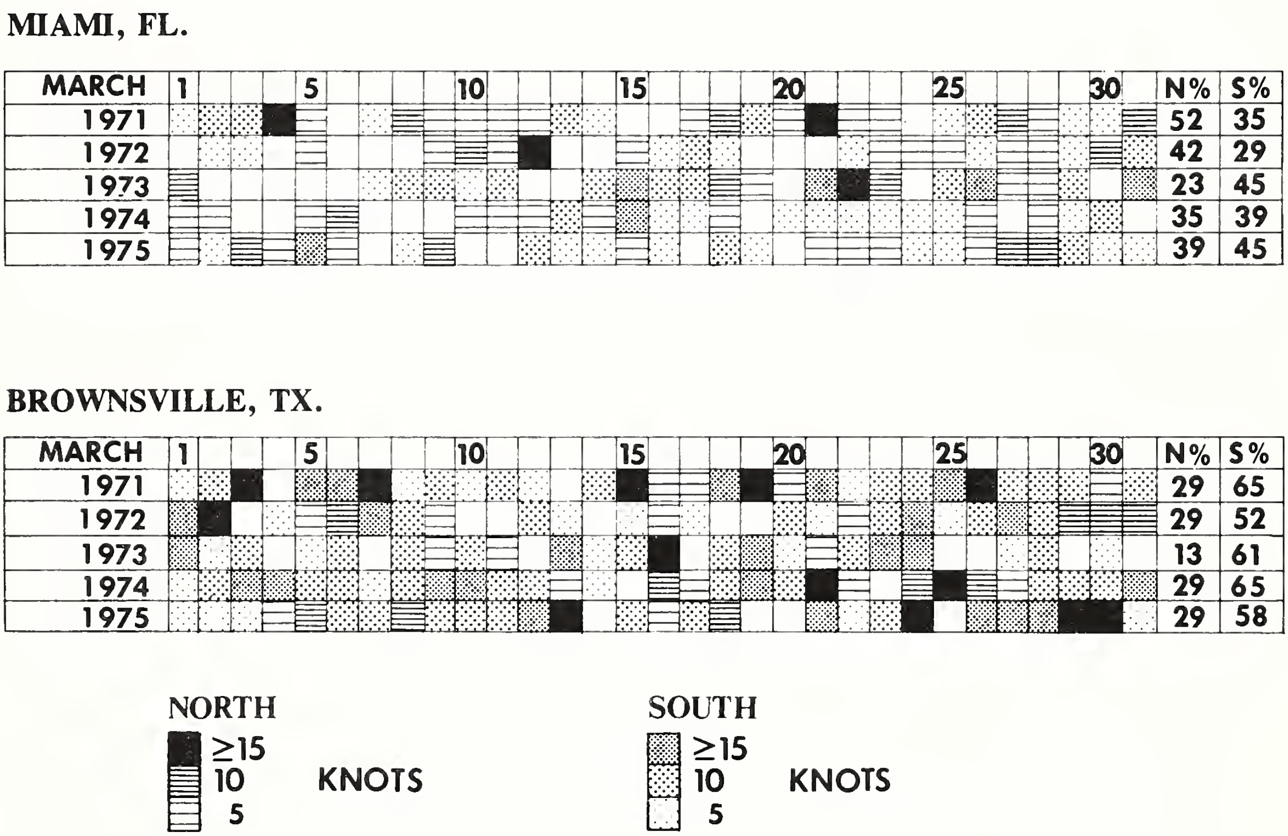

Figure 12
Southerly (transport potential to the north) and northerly (transport potential to the south) components of surface winds during March for 5 years at Miami and Brownsville.

variability from one March to another is considerable, but as represented by the data from Brownsville, each March appears to provide numerous opportunities for the transport of moths towards the north over southern Texas. A glance at figure 13 shows relatively similar frequencies and variabilities at Shreveport, even though the average frequency for transport potential towards the north is about 10 percent less at Shreveport than at Brownsville.

When we return to the two figures again to study the frequencies of southerly flow near the east coast at Miami and Atlanta, we see that opportunities are much less frequent there and the persistence is much less. Surface windspeeds also tend to be much lower than for the Brownsville-Shreveport axis. On the average during March, southerly flow occurred only about 40 percent of the time at Miami and about 33 percent at Atlanta. It should be obvious that climatic opportunities for rapid migration of moths towards the north in late winter and early spring are much greater over Texas towards the Great Plains and the lower Mississippi River Valley and not very great over the Coastal Plain east of the Appalachian Mountains. These climatic patterns may help to explain the very slow northward progress of fall armyworm moth catches from Florida into the Carolinas in spring (S. Pair, personal communication).

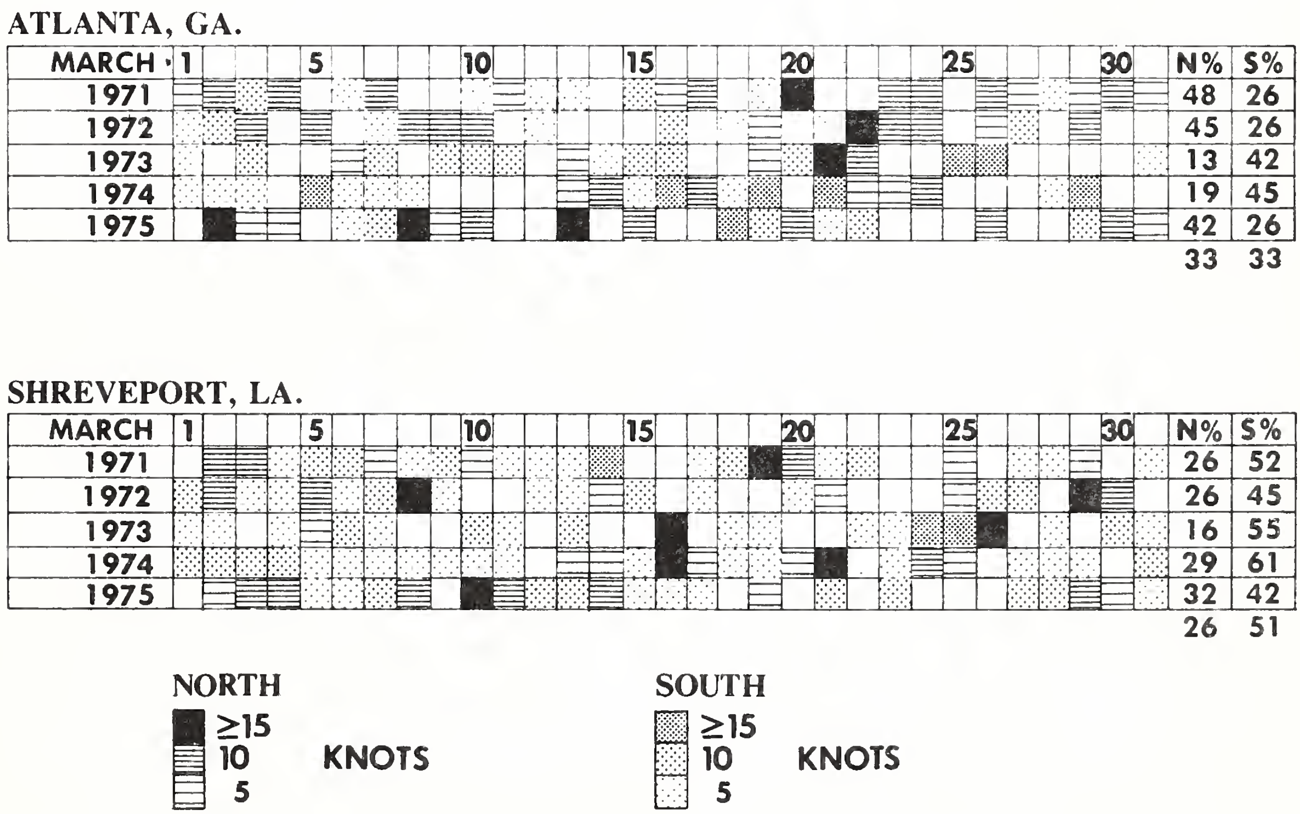

Figure 13
Southerly (transport potential to the north) and northerly (transport potential to the south) components of surface winds during March for 5 years at Atlanta and Shreveport.

Some entomologists are concerned that continual outmigration of a species, corn earworm moths for example, from northeastern Mexico or southern Texas would eventually diminish the instinct to migrate. Therefore, they raise the question about climatic opportunities for a return migration southward in late summer or fall.

Figures 14 and 15 show northerly and southerly airflow at Atlanta and Shreveport and Miami and Brownsville, respectively, for 5 years of Octobers between 1971 and 1975. At all four places, surface airflow from the north is greater than airflow from the south on the average during October. Inspection of the figures reveals, however, that northerly flow occurs on more than half the days on the average at Atlanta and Miami, but is much less frequent west of the Mississippi River at Shreveport and Brownsville. In the fall, the opportunities for insect migration towards the south are far greater over the Coastal Plain east of the Appalachian Mountains than to the west over the Mississippi River Valley.

In the fall, the climate would appear to be equally permissive for migration. It is possible, then, that moths not only migrate northward with the GR and FGR weather in late winter and spring, but

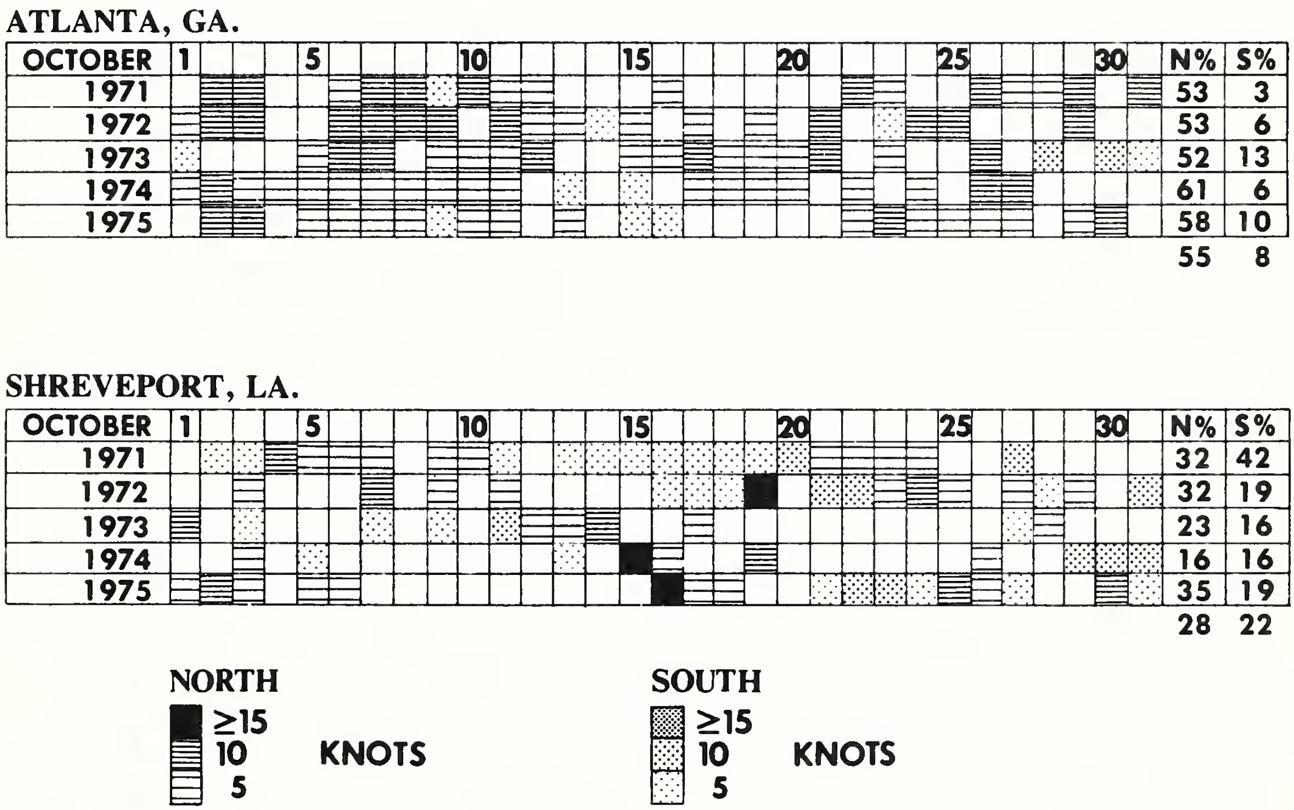

Figure 14
Southerly (transport potential to the north) and northerly (transport potential to the south) components of surface winds during October for 5 years at Atlanta and Shreveport.

also that later generations of moths migrate southward in fall during CH and FOR weather.

Climatic Opportunities for Migration Between the United States and Mexico

Not only does climate favor migration of moths north from the Southern United States, transport opportunities also exist that favor a closed cycle of circulation returning moths from southern Florida across Cuba and westward to the Yucatan in the fall and allow northward transport potential along the eastern coast of Mexico to southern Texas in late winter and spring.

Figures 16 and 17 show the geographical outline of the proposed "cycle" in subtropical latitudes, and summaries of pertinent climatic data are given in table 1. To assess atmospheric transport potential, we used the surface maps and 850-millibar charts of the National Meteorological Center, available on microfilm from the National Climatic Data Center. At the time of the analysis, we had available 4 years of maps, 1978-81, for March and 3 years of maps, 1978-80, for October. To compile the appropriate index of airflow, we included a 45°-azimuth sector on either side of the wind direction in question. For example, we were interested in airflow from the

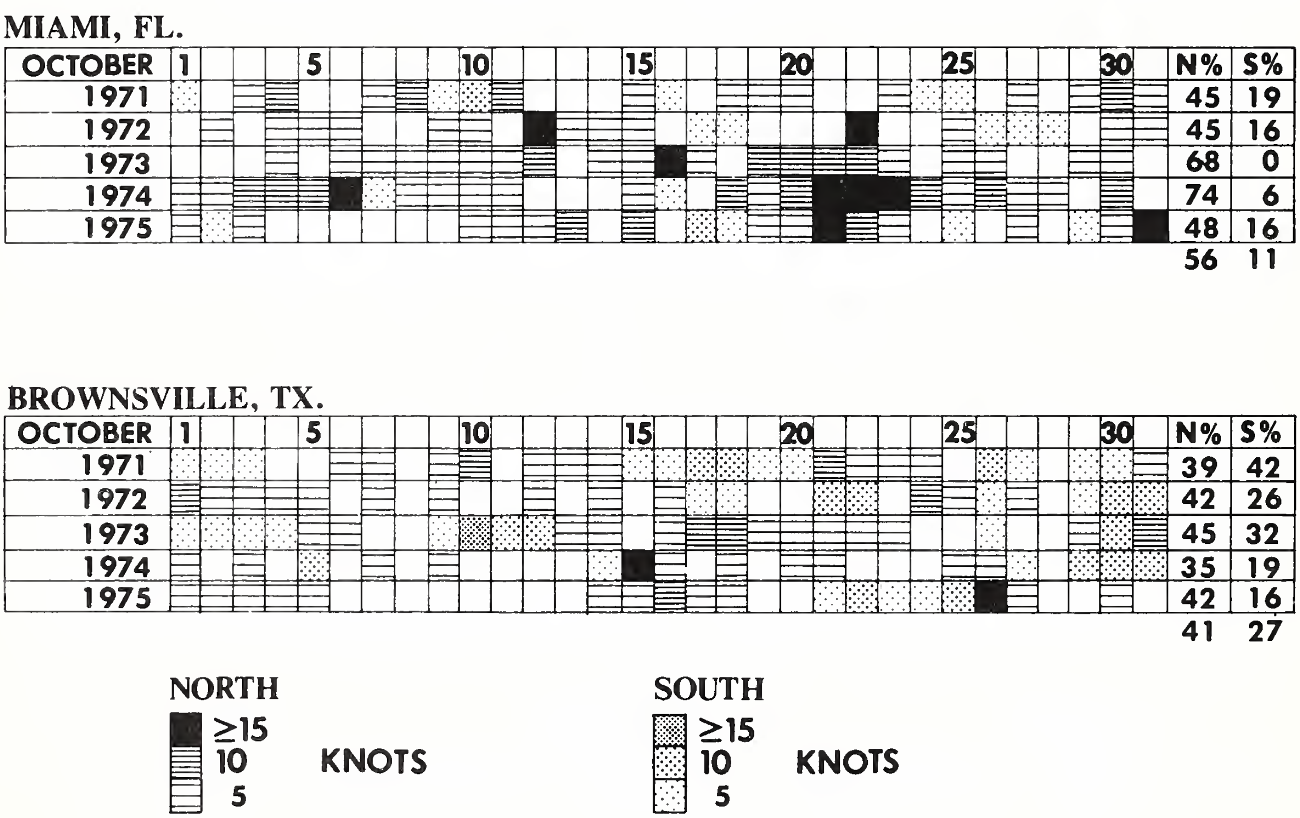

Figure 15
Southerly (transport potential to the north) and northerly transport potential to the south) components of surface winds during October for 5 years at Miami and Brownsville.

northeast (45° azimuth) during October at Key West, FL, so we included all cases when the wind was from any azimuth between 360° (north) and 90° (east). Because these weather maps have much more detail, we used a smaller sector than was used for the wind frequency and wind direction analysis in the previous section.

Figure 16 shows the pathway for potential migration southward during October, with data for Atlanta; Miami; Key West; Havana, Cuba; Grand Cayman, Bahamas; and Merida, Mexico, used to evaluate frequencies of favorable winds at the surface and aloft at the 850-millibar level. Note especially that we centered the 90° sector on the 360° azimuth (transport to the south) at Atlanta, on an azimuth of 45° at Miami, Key West, Havana, and Merida, and on 90° at Grand Cayman.

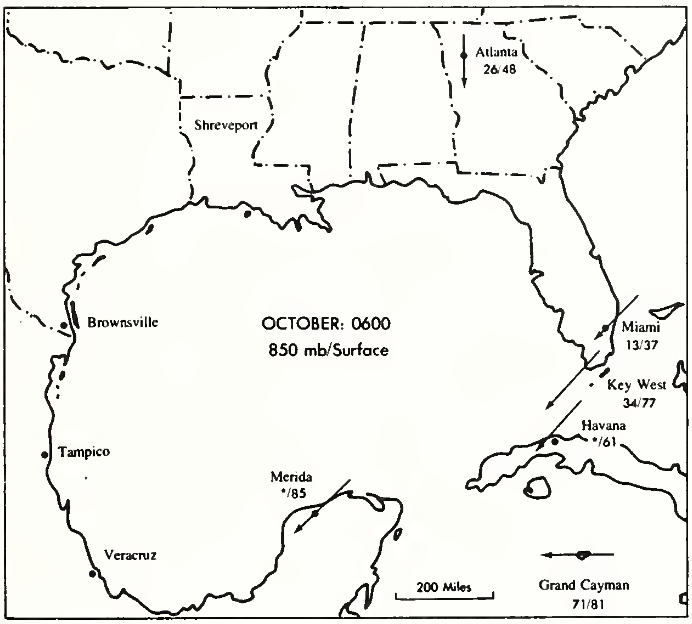

Figure 16
Pathway for potential migration of moths from Georgia and Florida to the Yucatan during October. The ratio shows the percent of time at the 850-millibar and surface levels when the transport opportunity was in the favorable direction shown on the map.

The "fractional data" shown in figure 16 represent the percent of time during October at 0600 hours CST when winds at the surface and at the 850-millibar level were from the sector of interest. Table 1 includes the same data as well as the number of cases and average windspeeds in knots. Perusal of the figure and table shows surface winds were from northerly or northeasterly directions more than a third of the time between Atlanta and Miami, but frequencies for transport towards the south at the 850-millibar level were considerably less.

South of Florida, however, the atmospheric circulation patterns strongly favor transport towards Cuba and eventually to the Yucatan; in these areas, favorable surface winds apparently occur between 60 and 85 percent of the time during October. Data for the 850-millibar level are not available for Havana or Merida, but the Grand Cayman data suggest strongly that there are increasing frequencies of winds from the northeast and east within the region of trade winds over the Caribbean Sea and adjacent waters. Within these latitudes, the potential for insect transport towards the west and southwest is present at the surface and 850-millibar level most of the time in October.

The open-water distances are not all that great. The distance across the Florida Straits from Key West to Cuba is only about 150 km, and assuming an average windspeed of only 10 knots with moths flying with the wind, the flight from shore to shore can be accomplished in only 8 hours. The Yucatan Channel between Cuba and the Yucatan is about 200 km wide, and assuming again an average windspeed of 10 knots, this more lengthy passage would require about 11 hours of flying time. But overwater flights of this length have been documented in the literature. Shaw and Hurst (1969) analyzed catches of adults of diamondback moth, Plutella xylostella (L.), which had crossed the

Table 1. Transport opportunities in the subtropics

Time, date, and place[1]	Level	Ratio of favorable days	Mean (%)	Windspeed (knots)
1800 CST				
March 1978-81				
Grand Cayman (90°)	850 mbar	57/108	53	13
	surface	77/97	79	10
Merida (45°)	850 mbar	no data	no data	no data
	surface	69/112	62	11
Veracruz (135°)	850 mbar	25/58	43	11
	surface	35/110	32	10
Tampico (180°)	850 mbar	no data	no data	no data
	surface	3/73	4	12
Brownsville (180°)	850 mbar	58/108	54	20
	surface	44/115	38	16
Shreveport (180°)	850 mbar	47/116	40	23
	surface	46/116	40	11
October 1978-80				
Atlanta (360°)	850 mbar	27/85	32	17
	surface	16/81	18	10
Miami (45°)	850 mbar	47/88	53	14
	surface	53/83	63	12
Key West (45°)	850 mbar	50/82	61	12
	surface	69/88	78	11
Havana (45°)	850 mbar	no data	no data	no data
	surface	55/63	87	9
Grand Cayman (90°)	850 mbar	55/75	73	12
	surface	33/40	83	10
Merida (45°)	850 mbar	no data	no data	no data
	surface	67/73	92	9
0600 CST				
March 1978-81				
Grand Cayman (90°)	850 mbar	66/104	63	14
	surface	79/95	83	10
Merida (45°)	850 mbar	no data	no data	no data
	surface	60/98	61	9
Veracruz (135°)	850 mbar	35/61	57	12
	surface	6/77	no data	10
Tampico (180°)	850 mbar	no data	no data	no data
	surface	0/19	0	no data
Brownsville (180°)	850 mbar	65/110	59	25
	surface	43/106	41	12
Shreveport (180°)	850 mbar	52/114	46	27
	surface	31/100	31	10

Time, date, and place[1]	Level	Ratio of favorable days	Mean (%)	Windspeed (knots)
October 1978-80				
Atlanta (360°)	850 mbar	22/83	26	14
	surface	39/82	48	10
Miami (45°)	850 mbar	32/86	37	12
	surface	39/81	48	11
Key West (45°)	850 mbar	27/80	34	11
	surface	62/81	77	11
Havana (45°)	850 mbar	no data	no data	no data
	surface	23/38	61	8
Grand Cayman (90°)	850 mbar	60/85	71	11
	surface	29/36	81	9
Merida (45°)	850 mbar	no data	no data	no data
	surface	28/33	85	7

[1]Figures in parentheses are the azimuths representing appropriate wind directions; for example an azimuth of 45° represents airflow from northeast to southwest.

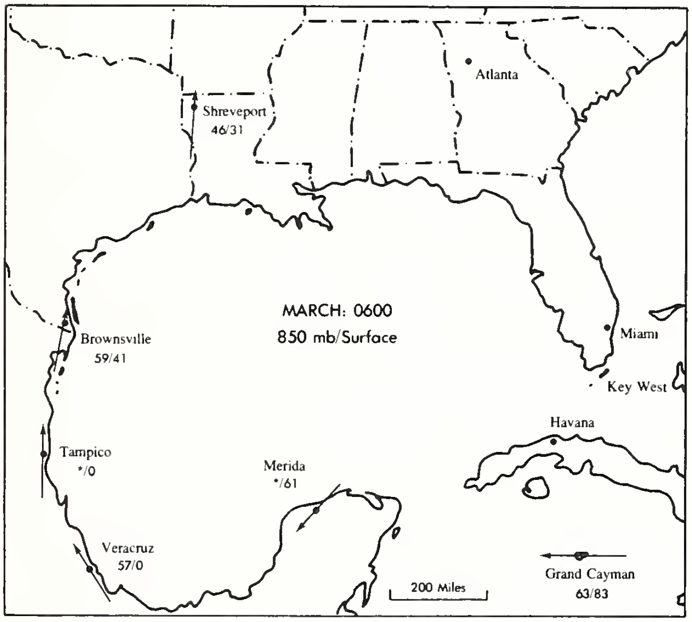

Figure 17
Pathway for potential migration of moths from southern Mexico into the lower Mississippi Valley during March. The ratio shows the percent of time at the 850-millibar and surface levels when the transport opportunity was in the favorable direction shown on the map.

Baltic and North Seas, and concluded that the moths were carried or migrated a distance of 2,400 km, mostly over open water, in 2 or 3 days. It does need to be kept in mind, however, that in the northern European weather situation, supporting winds would tend to be stronger than winds normally experienced over the Florida Straits and the Yucatan Channel.

Figure 17 suggests a pathway for moth migration in March along the Mexican coastal regions northward eventually to south Texas and the lower Mississippi River Valley. The analyses for Merida, Brownsville, and Shreveport strongly support the possibility of transport opportunity, but the data for Veracruz, Mexico, and Tampico, Mexico, are not fully supported. Both Tampico and Veracruz are coastal cities, and the wind data may be influenced strongly by local sea-breeze regimes. At Veracruz, for example, 32 percent of the surface winds at 1800 hours CST are from the southeast (favorable transport towards the northwest along the coast), but only 8 percent of the surface winds at 0600 hours CST are from the

southeast. However, the winds at the 850-millibar level are from the southeast 43 and 57 percent of the time at 1800 and 0600 hours CST, respectively. These combinations of surface winds and 850-millibar winds suggest a local sea-breeze regime superimposed on the regional winds along the coastline. It is likely, however, that regional transport potential towards the northwest is available.

At Tampico, however, there is very little surface data for 0600 hours CST and no data for any time at the 850-millibar level. An analysis of the total surface-wind distribution for 0600 and 1800 CST shows surface winds mostly from the northwest (from land to sea) at 0600 hours CST and from the east (from sea to land) at 1800 hours CST. Again, as for Veracruz, the data suggest a local sea-breeze circulation, and the general concept of overall regional transport potential towards the northwest is likely to be true.

Summary and Conclusions

This paper needs to be read as a status report, providing information about concepts that have been investigated for only a short period. The work of Hartstack and his associates in Texas strongly suggests that corn earworm moths are transported hundreds of kilometers towards the north in late winter and spring during weather situations that recur repeatedly over this climatic region. This study demonstrates that the thermal and wind properties at the surface and up to at least 1.6 km during these weather situations in March and April, GR and FGR weather, are favorable and supportive for moth flight. Similar favorable weather situations occur much less often over northern Florida northward into the Carolinas during late winter and early spring; so moth transport opportunities there are less frequent and persistent.

Climatic opportunities for transport towards the south are present during fall. The opportunities are more frequent and persistent over the eastern sections of the humid subtropical climatic realm of the American South, but opportunities do occur over the Mississippi River Valley and the Great Plains with trajectories towards southern Texas.

Finally, a closed cycle of moth transport is indeed possible, with transport potential towards the north in spring over Texas, the Great Plains, and the Mississippi River Valley, and towards the south in fall, mainly over the coastal plain east of the Appalachians to Florida. During the fall, climatic opportunities for atmospheric transport are present much of the time from southern Florida across western Cuba to the Yucatan, and then finally, along the Mexican coast back to southern Texas by late winter and early spring. It should be noted that a much more simple closed cycle is available between northeastern Mexico and southern Texas on the one hand and the central United States on the other, with transport completely over land towards the northeast in spring and the return towards the southwest again completely over land in the fall.

This paper includes both interpretations of interrelationships of climatic data with moth catches and speculation about long-distance transport. Whether in terms of transport or migration, the implications to the ecology and control of moth populations are wide reaching; indeed, there are implications for many other sectors of the insect communities. The transport and migration concepts need to be looked at carefully at this time, for the implications for regional if not continental integrated pest management as well as for the health of the entire plant and animal communities are considerable.

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RELATIONSHIP BETWEEN RADAR ENTOMOLOGICAL MEASUREMENTS AND ATMOSPHERIC STRUCTURE IN SOUTH TEXAS DURING MARCH AND APRIL 1982

W.W. Wolf, J.K. Westbrook, and A.N. Sparks[1]

Abstract

Favorable winds for movement of insects from northeast Mexico into the United States occurred during March and April 1982. An entomological radar detected *Heliothis zea* and *Heliothis virescens* sized insects moving with these winds. There was a significant correlation between layers of insects observed by radar and the altitudes of low-level wind jets. Mapping of transport-potential indices indicated the relative importance of wind circulation to northward movements. An insect-dispersion model was developed to simulate the dispersal of an insect population. The model used radar-derived flight behavior, population updates based on daily pheromone-trap catches, and smoothing of the wind velocity distribution at the appropriate insect flight altitude.

Introduction

Circumstantial evidence and release-recapture studies point toward spring movement of the corn earworm, *Heliothis zea* (Boddie), and the tobacco budworm, *Heliothis virescens* (F.), from northeast Mexico into the Southern United States (Raulston et al. 1982). A critical time for this movement is in the spring (Hartstack et al. 1982) before the emergence of local populations. Bonner (1965) reported that low-level wind jets occurred frequently in the Great Plains during the spring. These jets had convergence zones in northeast Mexico and central Texas with the axis of the jets directed toward the northeast. For the 28 jet cases he studied, the average speed of the level of maximum wind was 26 m/s. These jets averaged 500 to 800 m altitude near Oklahoma City, OK, and Fort Worth, TX, respectively. The convergence zones shown in Bonner's paper suggest that a low-level jet could transport insects toward the jet axis and increase insect displacement. Special-purpose radars have been used the past 10 years to provide information about insect flight. Schaefer (1976) described the use of inexpensive marine radars for entomological studies in Africa, Australia, and Canada. Observational and analytical procedures developed by Schaefer (1976), Riley (1978), and Drake (1981) allow rapid quantitative and qualitative measurements of insects at various altitudes.

The U.S. Department of Agriculture's Agricultural Research Service began a field program to investigate movement of the corn earworm and tobacco budworm from Mexico into the southern United States during March and April 1982. X-band radar equipment was used to monitor nocturnal insect activity for 2 weeks at Brownsville, TX, and 1 week at College Station, TX. Detailed surface observations of *Heliothis* spp. activity corroborated the airborne activity as determined by the radar measurements. This paper presents the synoptic situation during the test period, effects of atmospheric weather structure on insect flight behavior, and an insect-dispersion model.

Methods

Radar Equipment and Techniques

The radar system consisted of a Decca model RM-926 transceiver and display mounted in a surplus military radar trailer MPQ-29 fitted with a 1.22-m-diameter

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parabolic antenna (fig. 1). The transmitter operated at a wavelength of 3.2 cm (X-band), with a peak power of 25 kilowatts. Pulse lengths of 0.05, 0.25, and 1.0 microseconds could be selected for various observations.

Quantitative measurements of insect density (insects per 10^6 cubic meters) were taken by visually assessing the radar screen in a method similar to those described by Schaefer (1976) and Drake (1981). Insect densities were measured at different altitudes by pointing the radar beam at successive angles above the horizon. Insect-density profiles (density vs. altitude) were measured at 15-minute intervals during the early evening flights and at hourly intervals later during the night. Successive profiles were used to construct insect-density contour plots vs. altitude and time after sunset.

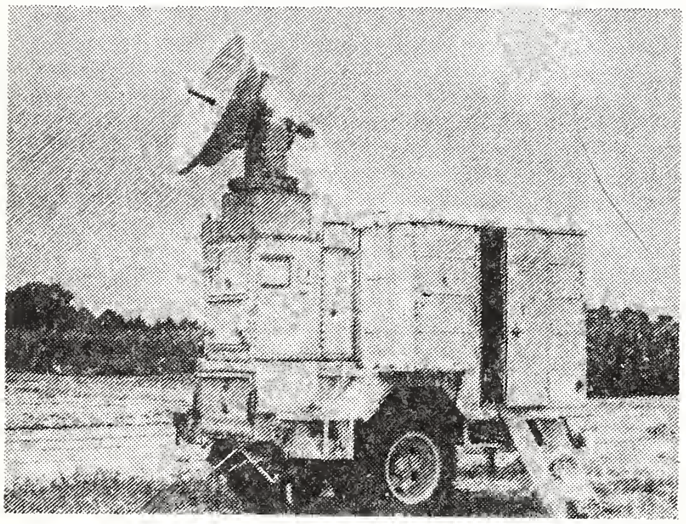

Figure 1
U.S. Department of Agriculture entomological radar system consisting of a Decca model RM926 X-band transceiver mounted in an MPQ29 radar trailer fitted with 1.22-m-diameter parabolic antenna reflector.

Meteorological Data Base

Meteorological data were obtained from the National Weather Service, onsite upper-air soundings (radiosondes), and surface weather observations. The National Weather Service data were obtained from 20 aerological stations (with radiosondes) and 171 surface reporting stations. Data from these stations were processed by the U.S. Department of Agriculture's Forest Service at Macon, GA, using their Forestry Weather Interpretations System (FWIS) (Paul 1981). The FWIS software ensured quality control, placed structured data into variable files, and archived the data. FWIS also produced hourly maps of meteorological variables such as temperature, windspeed, wind direction, sea-level atmospheric pressure, relative humidity, cloud cover, and current weather. Each map displayed State boundaries and an overlaid grid with the extrapolated variable printed at the grid intersections.

Atmospheric structure onsite (variation of atmospheric properties with altitude) was measured with a radiosonde attached to a helium-filled balloon. As the balloon ascended, the radiosonde transmitted wet- and dry-bulb temperature and atmospheric pressure to a ground receiver every 6 seconds. During periods when the radar detected insects, radiosondes were released at about 3-hour intervals and tracked with the radar to obtain windspeed (V) and direction. Telemetered data from the radiosondes were recorded on a Texas Instruments model 765 portable bubble memory terminal and transferred daily to a Hewlett Packard 9845 computer for archiving and computing atmospheric physical properties. Thus each radiosonde provided an atmospheric profile of altitude (Z) vs. temperature (T), dewpoint, absolute humidity, potential temperature (θ), mixing ratio, windspeed, and wind direction. Additional properties such as potential temperature lapse rate ($d\theta/dZ$) (thermal stability parameter), wind shear (dV/dZ)

(mechanical stability parameter), and atmospheric stability (log-transformation of the Richardson number = log $[(g/\theta)(d\theta/dZ)^{-2}]$) were used for the following analyses.

Aerobiological Statistics

Insect behavior such as flight initiation, flight duration, and flight altitudes was derived from radar observations. Insect distribution often became layered at a particular altitude during the night. These layers were correlated with atmospheric structure by pairing atmospheric properties at altitudes of maximum insect density with the respective atmospheric properties at the altitude of minimum insect density. These comparisons were made for insect-density profiles that showed at least one maximum and minimum. Use of the t-statistic allowed an estimation of the significance of the mean differences between paired values and was performed for each atmospheric property derived from radiosondes.

Meteorological Analysis

The twice-daily National Weather Service aerological soundings were used for regional analysis of atmospheric transport potential, wind trajectories, and a model of insect dispersion. The National Weather Service reported atmospheric soundings at 00[2] and 12 Z (around sunrise and sunset at Brownsville). Universal Standard time (Z) was used so calendar dates would not change during the night. The National Weather Service soundings, the FWIS gridded maps, and insect flight-behavior data were used for these analyses.

An index was devised to express the contributions of synoptic scale wind systems to northward transport. This index was assumed to be a function of air temperature and wind velocity. A northward transport-potential index (TPI) was defined as the product of the frequency of occurrence of northward-moving winds with above-threshold temperatures and the average speed of these winds. The TPI value was calculated as

$$\text{TPI} = v \times \text{freq}\ (v>0,\ T>12\ ^\circ\text{C})$$

where v was the meridional (north-south) wind component. The threshold temperature reported by Hartstack et al. (1982) for H. zea was 12 °C. TPI values were calculated at the surface, 500-m altitude, and an altitude corresponding to an atmospheric pressure of 850 mbar (about 1,500 m).

Wind trajectories were used to estimate relative displacements of insects flying at different altitudes. A modified (two-dimensional) form of the National Weather Service trajectory-prediction model (Reap 1972) was used. The designation of five computational iterations per trajectory smoothed the trajectory solutions. Since radar observations implied that most insects flew for about 5 hours per night, our trajectories were based on this nightly flight duration. Only mean wind displacements were considered; therefore, the trajectory points described the mean positions of an air parcel through time. The wind vectors were not corrected for relative insect airspeed vectors. Trajectories were calculated for surface, 500-m, and 850-mbar winds.

An insect dispersion model was developed to simulate dispersal of an insect population. The model used a grid size of 0.5° longitude by 0.5° latitude (at 30° latitude) and a time increment of 0.6 hours. The model required an estimate of the local moth population (moths per hectare). We estimated these populations by multiplying H. zea pheromone-trap

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[2] Universal Standard Time (Z) = Central Standard Time + 6 hours.

catches[3] by a factor of 100. Our results can easily be corrected for empirically determined correlations between trap catches and populations. The model was initialized and updated with population estimates based on daily trap catches. An exponential-decay function extrapolated nightly moth movement away from each location. We assumed that part of the population would not be available for dispersal on any given night (because of behavioral and mortality effects). Therefore, we assumed that 50 percent of the local population dispersed each night. Simulated dispersion was terminated at temperatures less than 12°C or after 5 hours. Successive *H. zea* trap captures were used to update the dispersion-model simulations.

Results

Radar Observations

Radar observations revealed information about flight initiation, insect density, insect layer formation, and flight termination. (Insect numbers referred to in this report include *Heliothis*-sized insects and smaller. Although birds were detected, the number was small compared with the number of insects present.) Changes in the number of airborne insects during the night indicated an average flight time of 5 hours. Results from the night of April 4, 1982, were selected for illustration instead of including all data for each night.

The radar often detected layers of *Heliothis*-sized insects. An insect layer is shown in the insect-density profile of figure 2. This layer had a tenfold increase in density at 400 m over the density at 200 m. Some insect layers increased in density, moved vertically, or separated into multiple layers. Insect layers occurred at a mean altitude of 520 m.

Contour plots of insect density vs. altitude and time after sunset illustrate the nocturnal variation of insect density (fig. 3). The plot in figure 3 represents a computed best-fit surface of 12 insect-density profiles. It shows an early evening flight initiation with rapid ascent to 600 m, formation of a layer within 2 hours after sunset, and descent of some of the insects beginning about 4.5 hours after sunset. No significant numbers of insects were detected at sunset. Individual insect-density profiles for this date showed sharp density gradients associated with insect layers. The contour plots did not have these sharp gradients and had other distortions near the edges of the plot because the contouring algorithm force-fit a smooth surface with minimum-error mean squares.

Synoptic Weather

The synoptic circulation at the surface and at the 850-mbar pressure level provided intermittent winds favorable for northward insect movement during March and April 1982. Interruptions were caused by passages of cold fronts accompanied by wind shifts and cool temperatures. Each interruption of the flow of air from the south lasted only 1 or 2 days from late March through mid-April 1982.

The first period of northward transport at the surface extended from March 28 until April 2. This transport period developed when a leeside trough (immediately to the east of the Rocky Mountains) pushed a high-pressure center eastward from the central United States and accelerated the southerly flow across Texas on March 28. An invading cold front was positioned at Midland, TX, by 12 Z on March 30. The cold front became a stationary front by

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[3] Pheromone trap collections provided by J.R. Raulston and A.W. Hartstack, both with the U.S. Department of Agriculture, Agricultural Research Service.

03 Z on March 31 and produced south-southeasterly flow over eastern Texas. A leeside low-pressure cell, coupled with the stationary front, transformed the system into a warm front extending from Del Rio, TX, to Shreveport, LA. This warm front moved quickly northward from Texas. An ensuing cold front proceeded to the Gulf of Mexico and stopped northward movement by midnight on April 2.

A brief second period of northward transport was started by the northward passage of a warm front across coastal Texas by 21 Z on April 4. A cold front entered eastern Texas by 15 Z on April 5 and reached the Gulf of Mexico by 00 Z on April 6 to stop this northward movement.

A third northward transport developed when a leeside low-pressure center, accompanied by a cold front through eastern New Mexico, enhanced the northward flow across southern Texas at 15 Z on April 7. Extensive fog was observed on the night of April 7, and the approaching cold front was aligned

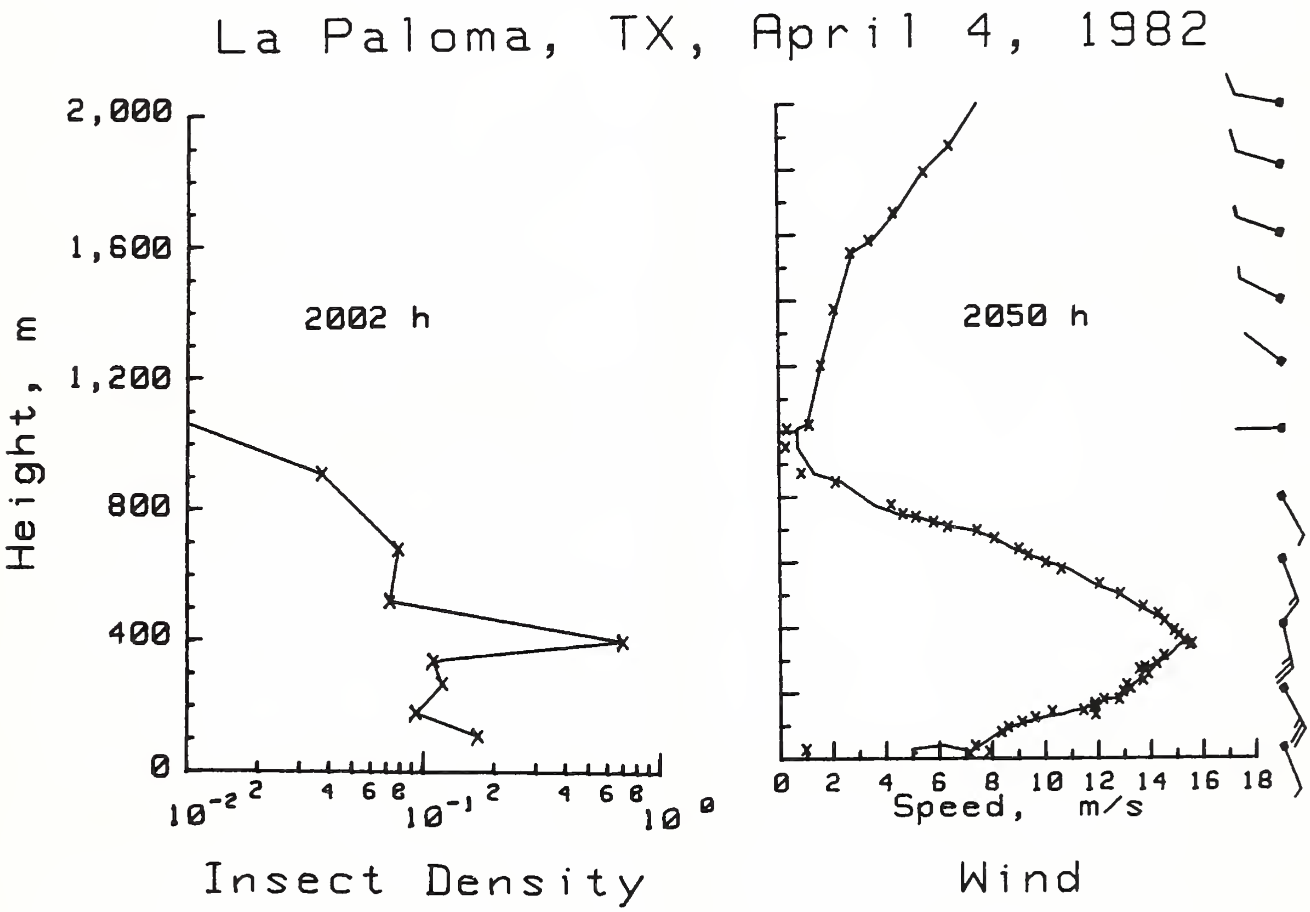


Figure 2
Examples of radar measurements of insect density (insects per 10^6 cubic meters) and windspeed and direction on April 4, 1982, near La Paloma, TX (20 km northwest of Brownsville, TX). Wind flags indicate wind direction at respective altitudes (2002 h = 0202 Z; 2050 h = 0250 Z).

through College Station and south of Del Rio, at 15 Z on April 8. A developing high-pressure center over Kansas decelerated the surface winds and created a disorganized flow across Texas.

The high-pressure center progressed westward to the Mississippi coast by 12 Z on April 12. This location of the high-pressure center supported northward flow across eastern Texas. The cold front transformed into a stationary front through Longview, TX, and Del Rio and enhanced northward flow by 00 Z on April 14. Atmospheric conditions became more moist and unstable through April 14. A National Weather Service tornado warning was issued for north-central Texas, valid from 00 Z to 04 Z on April 15. Warm temperatures and gusty winds characterized these unstable conditions.

Local Atmospheric Soundings

Radiosondes provided high-resolution measurements of atmospheric structure at the radar site. The importance of detailed information of the vertical atmospheric structure is evident in the April 4, 1982, soundings. Figure 2 illustrates a profile with significantly different winds at the surface, the altitude of insect maximum density (400 m), and at the 850-mbar level. Profiles of temperature, relative humidity, potential temperature (temperature

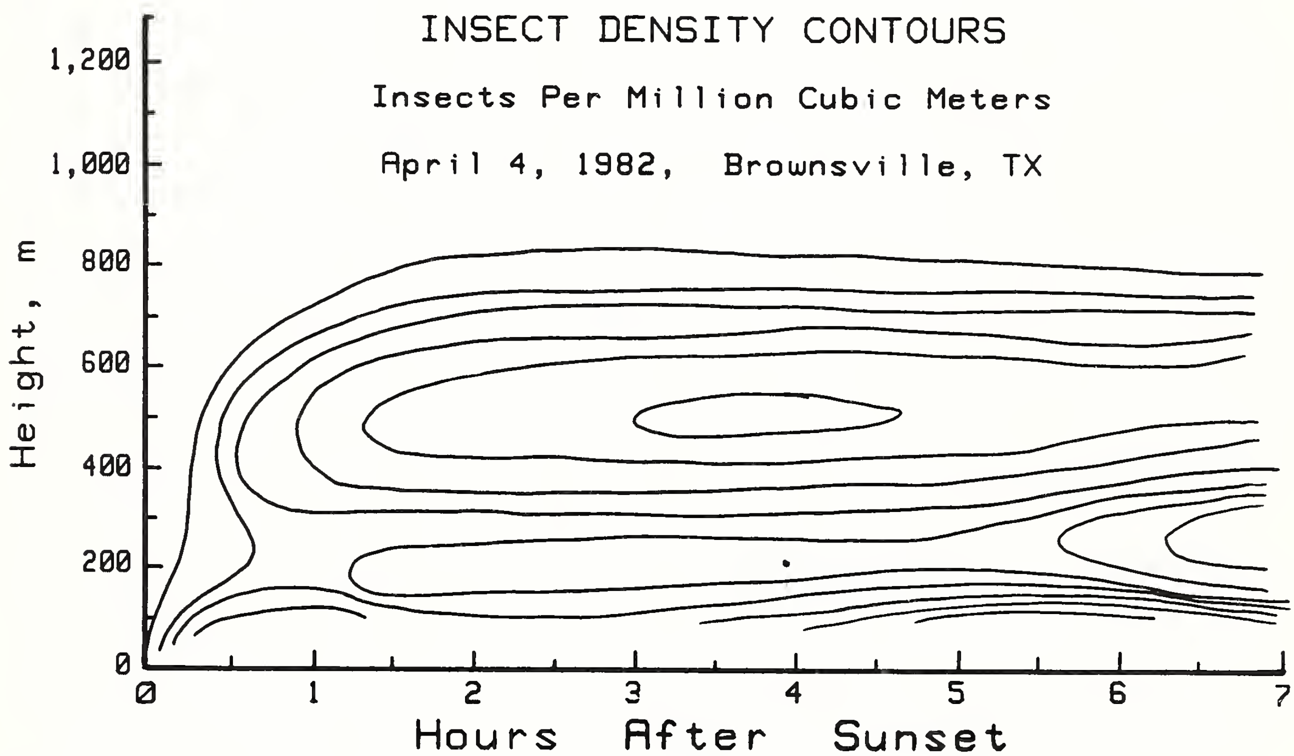


Figure 3
Contour plot of insect density (number per 10^6 cubic meters) vs. altitude and hours after sunset. Contours represent computed best fit fifth-order surface using 12 insect-density profiles during the night of April 4, 1982.

resulting when air pressure is adiabatically changed to 1,000 mbar), and mixing ratio are shown in figures 4 and 5. Each of these profiles revealed significant variations in vertical gradient.

The paired-value t-statistic tested the significance of atmospheric structure on insect flight. Neither temperature, dewpoint temperature, relative humidity, potential temperature, mixing ratio, nor wind direction significantly influenced insect-layer altitudes during these studies. However, the potential-temperature lapse rate was found to be significantly greater (more stable) at the level of maximum insect density. A significant speed difference indicated that layers occurred near altitudes of maximum wind. Significant differences in wind shear and atmospheric stability indicated that layers occurred in more stable air. These four significant parameters implied that the preferred insect-layer altitude approximated the centerline of the jet.

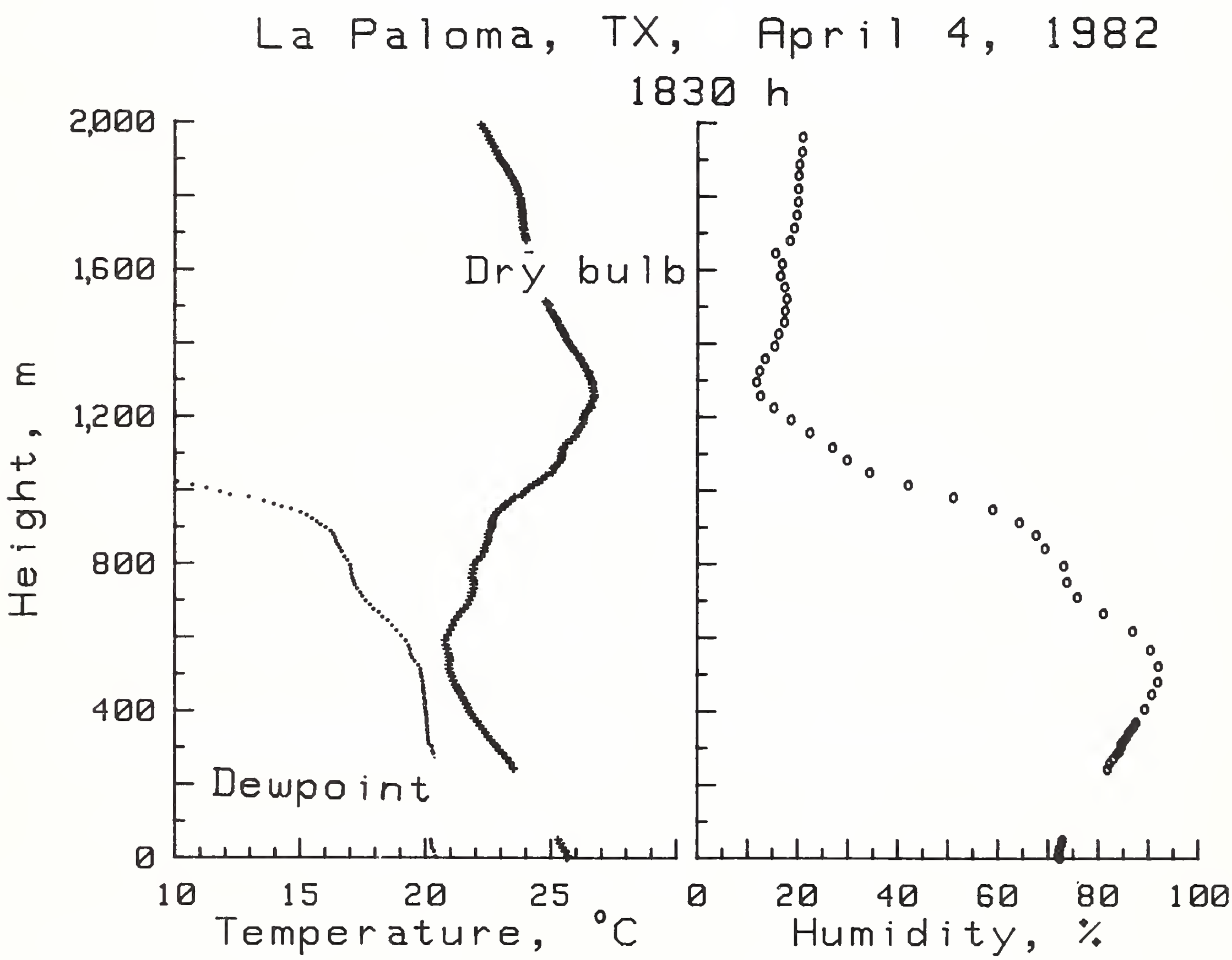


Figure 4
Examples of telemetered dry-bulb temperature and computed dewpoint temperature and humidity from radiosonde at 1830 hours, April 4, 1982, near La Paloma, TX.

Insect Dispersion

Atmospheric circulation was conducive to northward insect movement from southern Texas during March 28-April 2, April 4-8, and April 12-14. Maps of the northward transport potential at the surface, 500-m altitude, and at the 850-mbar pressure level are shown in figures 6a-6c. The greatest potential for northward migration extended along a corridor from Brownsville northward at 500-m altitude. The index for southerly flow diminished away from this corridor. Southwesterly circulation across northern Louisiana and Arkansas accompanied favorable transport conditions. Wind trajectories based on 5-hour insect flight duration and winds at 0-, 400-, and 1,500-m altitudes are shown in figure 7. Winds aloft opposed the surface winds (fig. 2) and caused the trajectories at the three altitudes to be markedly

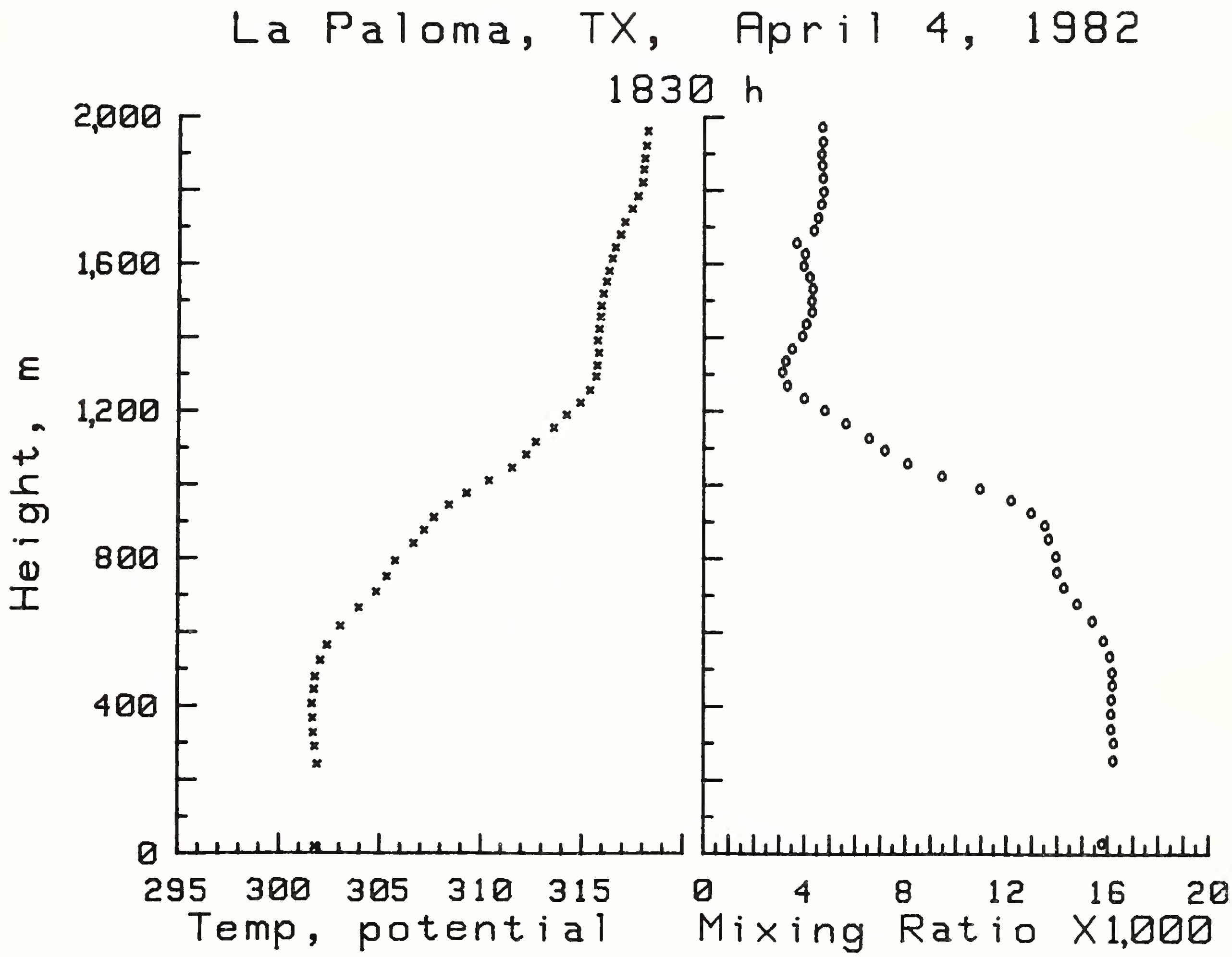


Figure 5
Examples of (a) computed potential temperature (temperature resulting when air pressure is adiabatically changed to 1,000 mbar) and (b) mixing ratio from radiosonde at 1830 hours, April 4, 1982, near La Paloma, TX.

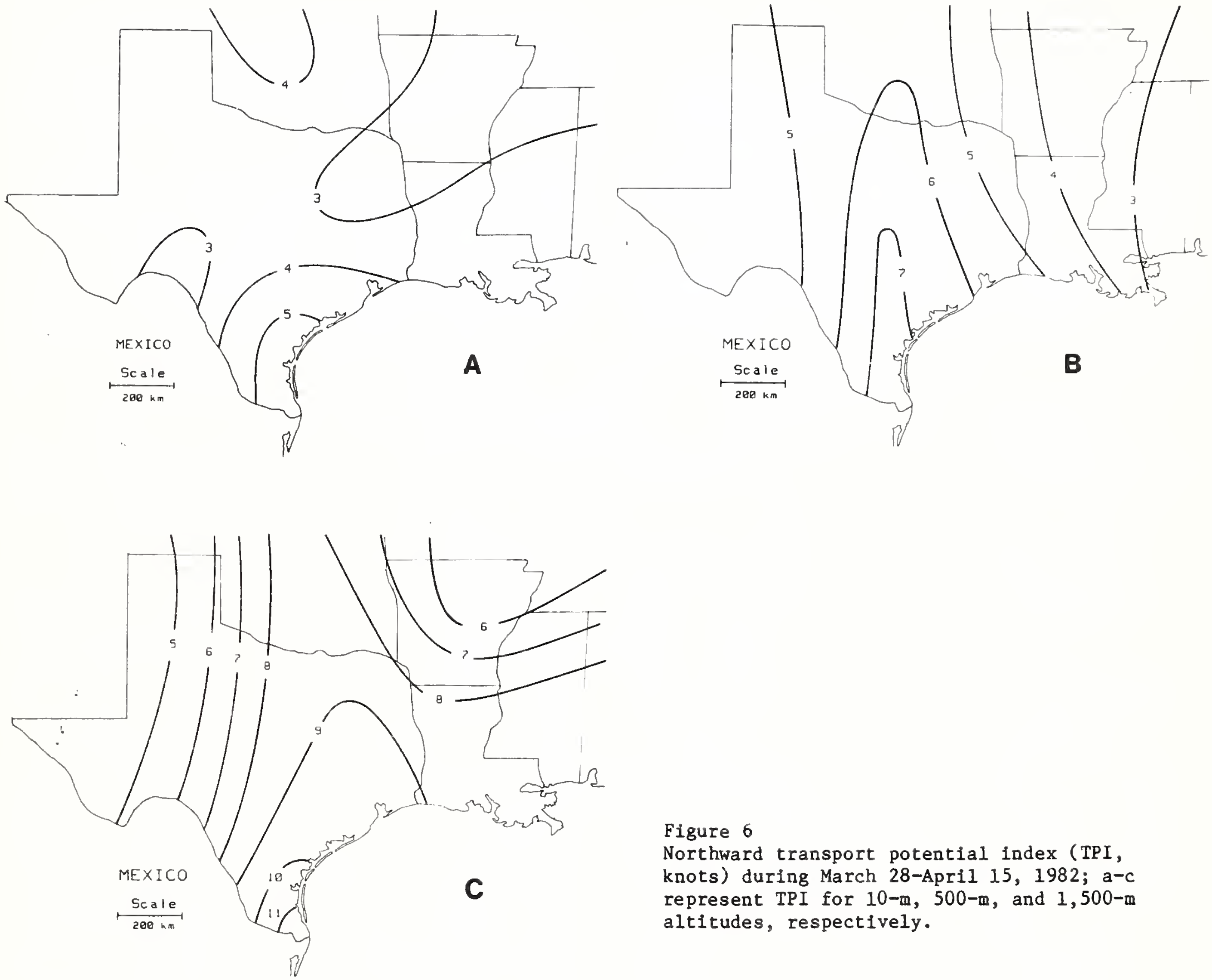


Figure 6
Northward transport potential index (TPI, knots) during March 28-April 15, 1982; a-c represent TPI for 10-m, 500-m, and 1,500-m altitudes, respectively.

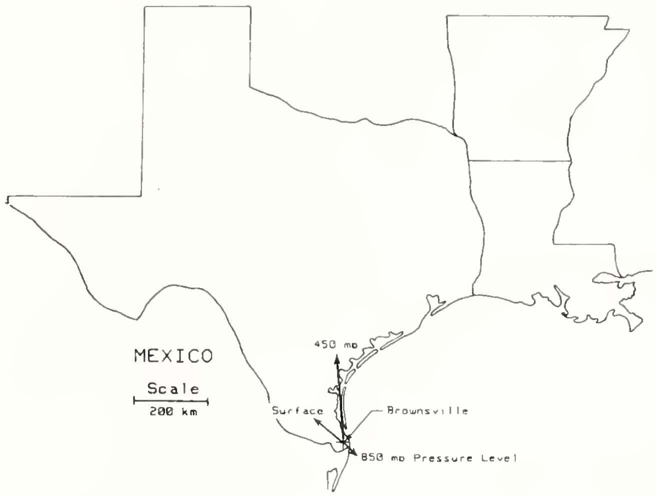


Figure 7
Five-hour atmospheric trajectories at three altitudes using winds from the 1250 Z radiosonde on April 4, 1982, near Brownsville, TX.

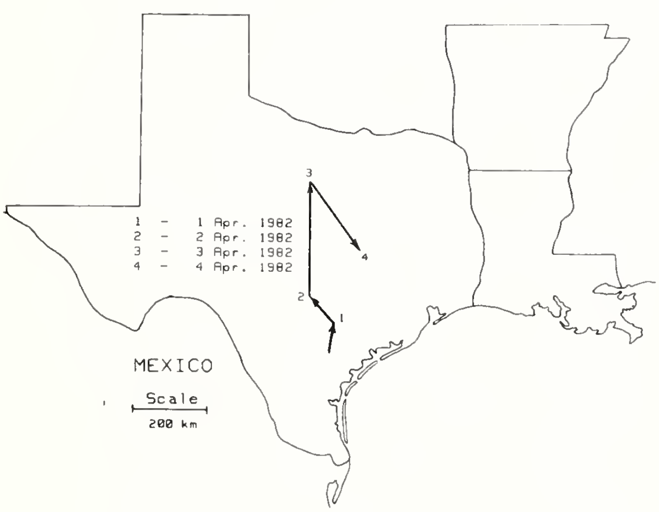


Figure 8
Trajectories for 4 successive nights using 500-m altitude winds interpolated from National Weather Service radiosondes. Each displacement started at 01 Z and terminated after 5 hours.

different. These trajectories demonstrate the importance of using meteorological values appropriate for the insect flight altitude.

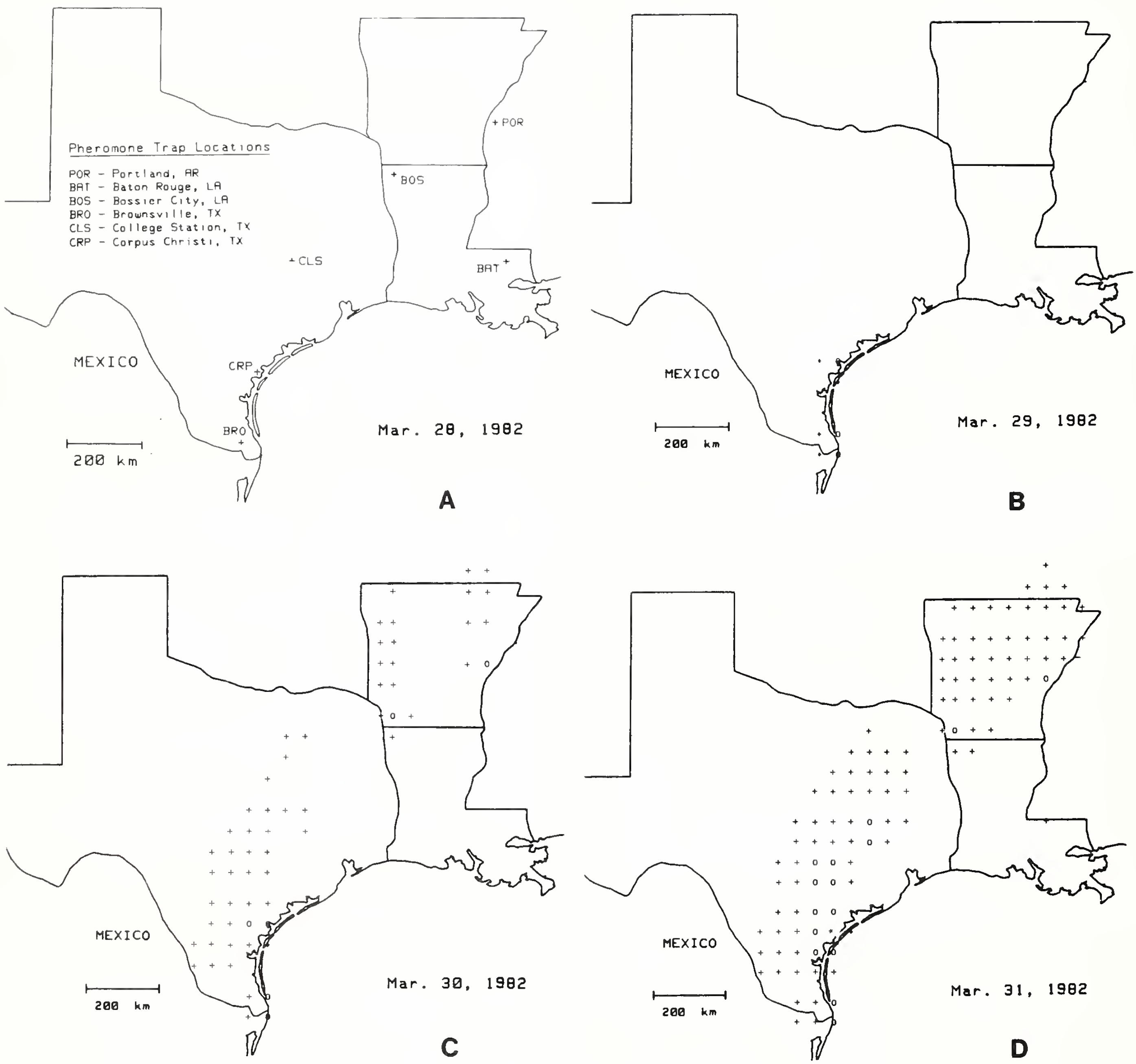
Wind trajectories based on average insect flight altitude, 5-hour flight time per night, and 4 successive flying nights are shown in figure 8. The displacement for the first 3 nights extended 360 km northward. We assumed no daytime displacement for these trajectories. The northward atmospheric transport accelerated from the March 30 starting date until April 2. A cold front then swept across Texas, and northwest winds produced 180-km displacement toward the southeast.

Simulated dispersions of *H. zea* populations from sources at Brownsville, College Station, and Corpus Christi, TX, Bossier City and Baton Rouge, LA, and Portland, AR, are shown in figures 9a-9h. The sequence of simulated *H. zea* migration patterns for March 28-29 revealed little dispersion because air temperatures were cool. Northerly transport with subsequent transverse spreading became more pronounced on March 30 and continued for the early part of April. The northward transport was especially accelerated on April 2 and April 4, before and after the passage of a cold front across southern Texas.

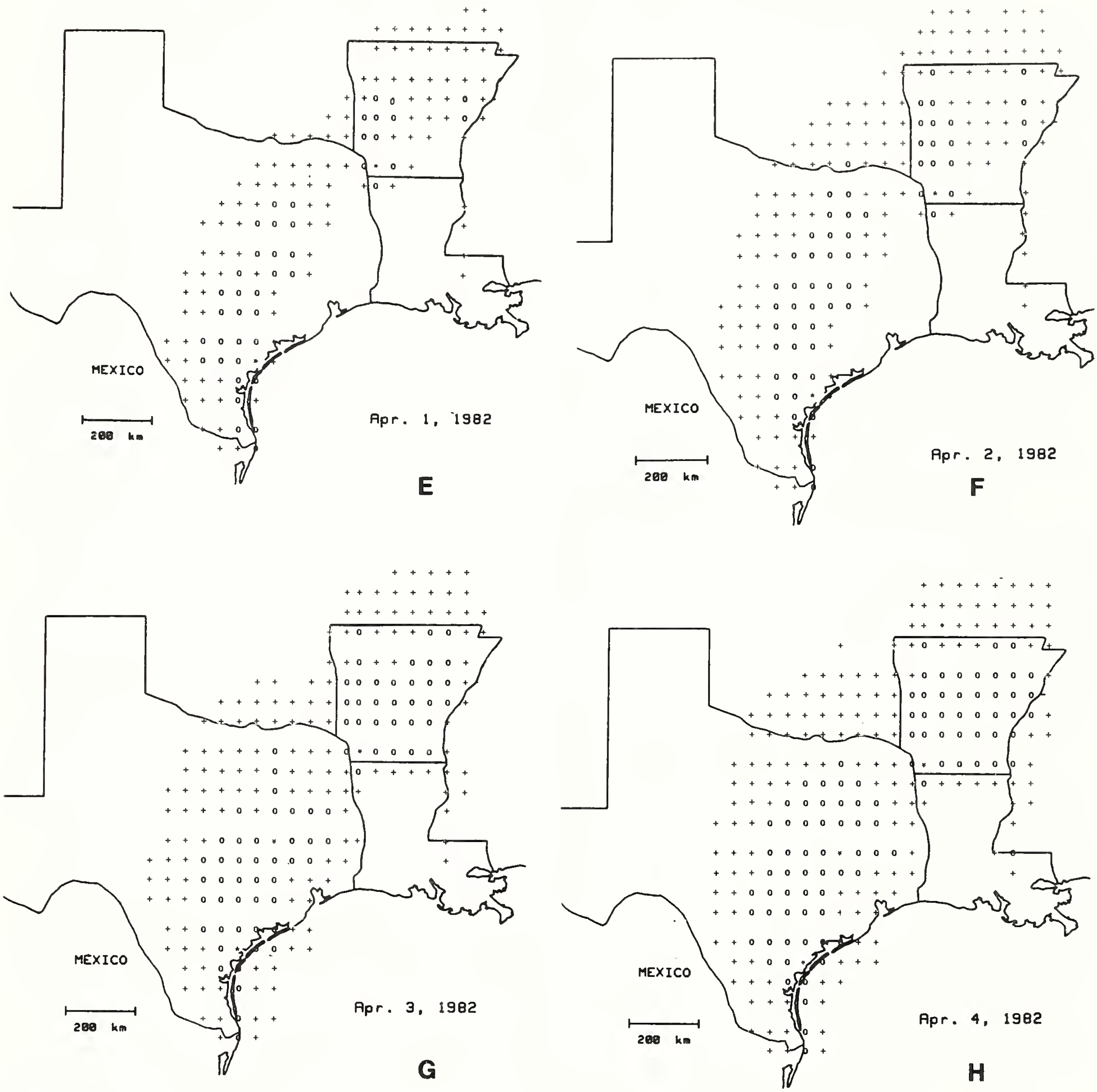
Discussion and Conclusions

The atmospheric analysis for the period of this study indicated favorable winds for insect dispersion from northeastern Mexico into the United States. The entomological radar detected substantial numbers of insects moving with these winds on warm ($T>12°C$) nights into south Texas.

Radar observations repeatedly indicated an early evening increase of insect flight with significant numbers ascending to 1,000-m altitude in less than 1 hour. The insect density at all altitudes tended to slowly decrease with time during nights



Figures 9a-9h
Computer-simulated dispersal of H. zea updated by daily pheromone trap catches from six locations in the Southern United States. Each of the eight figures represents a successive nocturnal diffusion of the moth populations, starting at 01 Z, flying at 500-m altitude for 5 hours each night. Insect concentrations were + = 10 moths/ha, 0 = 100 moths/ha, and * = 1,000 moths/ha.


MEXICO
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when no insect layers were detected. This slow decrease of insect density suggests a descent of part of the airborne insect population. The correlation between the radar-derived insect-density profiles and the atmospheric profiles implied significant atmospheric effects on insect flight. The formation of insect strata was often detected by the radar (at a mean altitude of 520 m) and was associated with specific meteorological conditions. The nocturnal insect layers were within atmospheric regions of enhanced thermal stability and lesser wind shear, and the insect layers often coincided with the low-level jet. The average windspeed at the level of maximum insect density was 2.4 m/s greater than the windspeed at the height of minimum insect density.

When insect layers were detected, the layering began within 3 to 4 hours after sunset, and on at least 2 nights, the layer persisted until dawn. The time of layer formation and the position of layers near the centerline of low-level jets suggested that the physical properties of these jets contributed to layer formation or that the insects detected and chose to fly in the jets.

The properties of the wind at various altitudes and the flight behavior of the insects will determine the final dispersion from the source. An insect with 5 m/s airspeed, flying for 5 hours in a 20-m/s wind, could travel 450 km per night. The direction and distance depend on cumulative wind vectors and insect airspeed vectors during the flight. Insect airspeed and orientation decreasingly affect displacement as the windspeed increases.

Our simulation of insect dispersion incorporated only the duration of flight, the average flight altitude, best estimates of winds at this flight altitude, and suitable flight temperatures. Special high-resolution measurements of the wind profiles on site were necessary because standard National Weather Service radiosondes were scheduled only at sunset and sunrise (at these longitudes), and winds at insect flight altitudes often accelerate during the night. Bonner (1965) reported that winds above the first few tens of meters and below 2 km may show a diurnal oscillation exactly opposite to that of the surface winds. We also detected significantly different winds at flight altitudes during the night compared with the 00 Z Brownsville National Weather Service atmospheric sounding.

These studies have demonstrated the importance of incorporating insect behavior and appropriate meteorological information into insect-dispersion models. Use of standard National Weather Service soundings can be misleading if they do not represent conditions at the altitudes and times of insect flight. Subtle insect behavior can significantly affect the displacement during a particular flight. The flight altitude, takeoff time, flight duration, and wind vectors most greatly influence displacements.

Further studies should include other insect behavioral traits in dispersion models and additional relationships between atmospheric structure and insect flight and determine frequency of occurrence and sizes of meteorological events favorable for insect dispersal.

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ECONOMIC IMPLICATIONS OF LONG-RANGE INSECT MIGRATION

Alton N. Sparks[1]

Abstract

Movement of highly mobile insect pests of agricultural crops is a major factor of concern in the development of strategies for control of such species. Yet this movement is little understood and not sufficiently researched. This paper suggests the development of an offensive strategy of pest control by attacking highly mobile species at the time and in the space of the pests' lowest population density. The rationale for the offensive strategy is shown via examples of potential economic values of similar programs.

As agriculture developed into an intensive economic business, entomologists implemented, and continue to deploy, a defensive strategy in efforts to control most of our insect pests. With this defensive concept of pest management, growers forfeit willingly some of their crops to insects until a designated threshold population level is observed and then grudgingly yield varying quantities of potential profit to the pests with efforts to annihilate them on a field-by-field, crop-by-crop basis. Even then, additional crop damage is experienced because of miscalculations and inabilities to achieve complete control. An alternative is to develop an offensive strategy--that is, attack insect pests on an area-wide basis. This strategy involves identifying major weak links in the pest species life cycle and attacking the pest at its lowest population level before its annual population density increase and dispersal over a much larger range.

In most cases, whether attempts to manage insect pests are made field-by-field or on an area-wide basis, insect migration is a major problem encountered. If entomologists are to fulfill their obligations in the agriculture industry's responsibility to supply food and fiber for an ever-expanding world population, then they must begin to understand these concepts.

In actuality, experimental data documenting long-range movement of agronomic insect pests in the United States are scarce. In early efforts, Glick (1939, 1965) used an airplane equipped with nets to sample airborne movement of insects. Luginbill (1928) used infestation records to estimate average dates for first appearance of particular species at varying degrees north latitude. In the past two decades, several experiments have documented extensive insect movement. Callahan et al. (1972) captured 9 orders and 35 families of insects in blacklight traps located from 85 to 320 m above the ground on a TV tower in south Georgia. Corn earworm, *Heliothis zea* (Boddie), amounted to 315 of 384 and 90 of 158 insects captured at 320 m throughout the growing seasons of 1967 and 1968, respectively. Snow et al. (1969) radio-labeled *H. zea*-infested corn plants on St. Croix and discovered that the corn earworm distributed itself over the entire 218-km^2 island wherever host plants were suitable for oviposition. Later, Haile et al. (1975) captured adult *H. zea* and tobacco budworm, *Heliothis virescens* (F.), which had been reared in the laboratory and internally marked, on the islands of Vieques and St. Thomas, 67.6 km NW and 61.2 km N, respectively, of St. Croix, where they had been released. In 1974, Sparks et al. (1985) captured 177 species representing 69 families and 9 orders of insects in blacklight traps mounted on 4 unmanned oil platforms up to 161 km into the Gulf of Mexico, due south of Jeanerette, LA. Sparks (1979) listed 14 species of Lepidoptera of economic importance captured during these studies. Collectively, these data document that many species of Lepidoptera of economic

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importance regularly fly at altitudes of at least 320 m and distances of at least 161 km nonstop.

In recent years, the U.S. Department of Agriculture's Agricultural Research Service has begun to research the variables of migration of highly mobile insects of agricultural importance. A thorough knowledge of the biology-ecology and population dynamics of these highly mobile species in their overwintering habitat and an understanding of their migratory habits could lead to the exploitation of weak links in the insects' life cycle during a time when the population is severely restricted by biological-climatological phenomena. Were this possible, populations of some migratory pest species could conceivably be suppressed to noneconomic significance.

The fall armyworm, Spodoptera frugiperda (J.E. Smith), is an example for which a research project encompassing those ideas has been started. The insects of the Heliothis complex are other species for which these principles of insect control could be highly beneficial.

The fall armyworm is a persistent pest of several agricultural crops throughout the Southeastern United States and along the Atlantic seaboard. It is a perennial pest on corn, sorghum, and improved pastures and is one of the primary factors that limits double cropping of grain crops in the Southeast. Populations of the fall armyworm have been estimated to reduce the income of farmers by $200 million to $300 million annually. In 1977, the fall armyworm developed into a serious problem throughout most of its summer range. Outcries from farmers reached politicians and resulted in partial funding of research designed to determine the feasibility of controlling this pest in its overwintering area before its annual buildup and subsequent migration northward throughout the United States into southern Canada. The restricted overwintering area of the fall armyworm in the United States, limited by the insect's inability to survive sustained temperatures below freezing, renders it susceptible to area-wide management.

Migration is a major factor of consideration. Extensive pheromone trap and larval survey data document first appearance and seasonal population trends for the fall armyworm in Florida, Georgia, Alabama, and South Carolina. Additionally, a cooperative team of entomologists, a radar engineer, and a meteorologist have been assembled to study insect migration and to model a weather-driven insect transport system. A substantial quantity of the team's efforts is directed toward the fall armyworm.

The fall armyworm is an excellent target for an area-wide management program. Techniques and information generated through research will be applicable to area-wide management of numerous other lepidopteran pests. Knipling (1980) discussed the desirability, feasibility, and potential economics of the approach. He suggested that fall armyworm area-wide management in its overwintering area could involve several suppressive measures and estimated costs at $5 million to $10 million annually. These costs are considerably lower than the estimated insecticide costs of $15 million and total direct losses averaging $300 million annually caused by the fall armyworm.

The corn earworm and the tobacco budworm are examples of other highly mobile insects of tremendous economic importance to agriculture. These species overwinter as pupae in the soil and in the case of the earworm, below 45° N latitude. However, several studies have indicated that overwintering survival is relatively low (<5 percent) even at a latitude as far south as 30° N (Phillips and Barber 1929, Barber 1941, Blanchard 1942, Stadelbacher

and Pfrimmer 1972, Slosser et al. 1975). Adults overwinter in the southernmost tip of Florida and in southern Texas in some years. As with the fall armyworm, these species expand their distribution themselves throughout the Cotton Belt each year, and the corn earworm causes extensive damage to sweet corn and other vegetable crops as it moves northward along the eastern shore into Canada. These two species plus the boll weevil, Anthonomus grandis grandis (Boheman), are credited with receiving 80 percent of the pesticides that are used on cotton and 60 percent of all pesticides that are used in the United States. Estimated losses and control costs for the Heliothis complex in the United States run into the hundreds of millions of dollars annually.

Data presented by A.W. Hartstack and others (in "Early Season Occurrence of Heliothis spp. in 1982: Evidence of Long-Range Migration by Heliothis zea," elsewhere in this book) indicate that populations of corn earworm adults appeared in northeast Texas, northern Louisiana, southeastern Arkansas, and northwestern Mississippi before the emergence of adults from pupae diapausing in the soil at College Station, TX. J.R. Raulston recently estimated (unpublished data) that 1.12 billion corn earworm adults and 1.67 billion fall armyworm adults emerged from 215,000 ha of corn grown in the spring in northeastern Mexico and the lower Rio Grande Valley in Texas. Do these emerging populations add formidably to the seasonal dynamics of endemic populations throughout the Southern United States? And if so, is there a possibility of cooperatively working with Mexico to suppress H. zea in northeast Mexico and the lower Rio Grande Valley in Texas to reduce U.S. costs of control and losses caused by this species?

There are formidable problems associated with a transition from current defensive management practices to offensive area-wide management strategies within overwintering habitats of insect pest populations. The technology required for area-wide management of insect populations demands thoroughness and precision in its application; and the organization, financing, and execution will create special problems.

One of the most important limitations will be the costs and difficulties involved in demonstrating that pest populations can be effectively managed over large areas. Until demonstrated to be effective and economically advantageous over current practices, the validity of the area-wide management concept must be viewed with skepticism.

Many uncontrollable variables influence results of pest management trials, especially when experiments are undertaken on a small scale and during a short period. Those who question the feasibility of area-wide management stress the need for more information on species' biology, ecology, behavior, and population dynamics before considering area-wide management programs. However, much of the information desired to reach a conclusion on the feasibility of area-wide management of pests is difficult and costly to obtain and may require years of research. And ecological studies in a small area over a short period may not provide the information needed and may lead to erroneous conclusions, especially if highly mobile pest or beneficial insects are involved. Pilot programs may be the only way to determine the feasibility of area-wide management. Therefore, justifying major research support on area-wide or ecosystem management techniques and strategies is difficult and complex.

Complications associated with area-wide management of insect pests are directly related to the degree of complexity of the pest situation in time, space, and ecological niche. For example, efforts to

manage insects of corn in Iowa are less complex in relation to the number of species, time of occurrence, continuity of space, and diversity of ecological niches than efforts of entomologists to manage corn insects in the Southern States. The realistic view appreciates the rare opportunity to manage a single pest of a single host and realizes that most typical pest problems involve a complex of pests that occur on more than one host.

Successful area-wide insect management programs have demonstrated remarkable estimated savings. The eradication of the cattle tick, Boophilus annulatus (Say), (Ellenberger and Chapin 1932, MacKeller 1942) and the consequential elimination of Texas fever are estimated to have saved the livestock industry $10 billion and resulted in accrued economic benefits of $100 billion to the Nation's economy (Knipling 1978). Other documented successful area-wide projects include the annihilation of the Mediterranean fruit fly, Ceratitis capitata (Wiedemann), from Florida four times since 1929 (Eden 1978). Knipling (1978) estimated that the 1956-58 program cost about $12 million from which a savings of about $200 million annually is realized by the fruit and vegetable industry. The eradication of the screwworm, Cochliomyia hominivorax (Coquerel), from Florida was estimated to cost $10 million, and accrued benefits have exceeded $1 billion in Florida alone (Knipling 1978).

An overview of the past and potential distribution of the screwworm and the current efforts to limit losses to the livestock industry in the United States and Mexico leaves no doubt that this program is a model of area-wide pest management. Proponents of the program must admit some uniqueness of screwworm behavior that renders it more susceptible to area-wide management than most other insects to be considered for such a program. Drastic reductions in natural populations of the screwworm due to its susceptibility to cold temperature, its adaptability for mass rearing, its susceptibility to ionizing irradiation with minimal effect on competitiveness, and its relatively simple interrelationship with other pests of warmblooded animals are pluses favoring area-wide management. However, other pests also have unique developmental behavior patterns that favor area-wide management using complementary integrated techniques.

Opponents of the screwworm program point out that infestations continue to occur in the Southwestern United States annually. However, the few sporadic and generally isolated infestations that occur have been eliminated without evidence of reestablishment of populations. In FY 82, the Governments of the United States and Mexico invested about $44 million in the screwworm program, splitting the costs at 80:20, with estimated savings to the livestock industry of $300 million and $100 million for the United States and Mexico, respectively (J.W. Snow, personal communication). In justifying such investments in managing a pest on a year-to-year basis, it is necessary to consider the costs and benefits of alternatives. Although it is impossible to state confidently what losses would have been had the program not been in force, it should be recognized that the program is a sound, economic pest management program for which we have no viable alternative.

Burrows et al. (1982) attempted to document the costs of failing to prevent the entry of the pink bollworm, Pectinophora gossypiella (Saunders), into California's Imperial Valley in 1966. Their cost analysis for the years 1966-80 indicate that total costs as a percent of crop value varied from a low of 8.04 percent in 1966 to a high of 79.59 percent in 1977. Estimates of actual dollar losses for the 15-year period ranged from

$1,588,000 in 1966 to $48,519,000 in 1977, averaged $10,571,000, and totaled $158,571,000. These data demonstrate the potential economic advantage of limiting or preventing the expansion of a pest's distribution. Also, these data indicate how much could be invested annually in management of the pink bollworm for the purpose of keeping them suppressed to subeconomic population levels.

Opponents of area-wide management of insects say it is prohibitively expensive and scientifically unsound or technically difficult to achieve. Proponents counter that area-wide management of some species of pests has resulted in monumental savings, and research to implement the management concept on other important species should be enhanced. All agree that with highly mobile species, such as those discussed in this book, migration is a major limiting factor to area-wide management that must be researched and understood.

The mechanisms that trigger migration in the species discussed here are unknown. Lingren et al. (1982) reviewed the status of research on nocturnal behavior of insects and reported that part of the population of any particular species of nocturnal (and perhaps diurnal) insect takes flight within an hour of dusk. Radar and weather information indicate the insects disperse at varying heights and directions but generally in a direction with the wind. Thus, on any given night during the crop-growing season, the airborne insects are available for long-range transport if the weather system is appropriate. Otherwise, these airborne insects move varying distances with the prevailing wind, only to "drop out" from within an hour after take-off up to just before sunrise. The following evening at dusk, portions of the population that were transported the previous night are joined by other insects and are transported again. This is a built-in mechanism to ensure survival.

In summary, defensive vs. offensive strategies of pest management have been discussed briefly. Through the use of selected examples, the speakers at this symposium have projected the thesis that area-wide management of pests is theoretically both economical and feasible. Philosophically speaking, area-wide management of pests that results in less contamination of the environment while providing the people of the world with adequate food and fiber is a strategy preferred over the currently used crop-by-crop, field-by-field defensive tactic. The practicality of any area-wide management program will only be determined after the scientific, administrative, farming, political, and tax-paying communities decide the time is right and actually conduct an area-wide program.

The interest exhibited and the data presented by this group of scientists should increase interest and research on insect migration. The entomological data generated a vast amount of high-quality circumstantial evidence to document long-range migration. Techniques that will define areas of origin and host plants fed on by migrating species must be developed. The meteorologists demonstrated the availability of weather patterns for insect transport. The radar data indicated that insects are certainly airborne and moving.

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☆U.S. GOVERNMENT PRINTING OFFICE: 1986- 622-467/345